Determination of Moment-Deflection Characteristics of Automobile Seat Backs

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1. Introduction

Federal Motor Vehicle Safety Standard (FMVSS) 207 - Seating Systems, went into effect in 1968 for passenger cars. It was extended to MPVs, trucks and buses in 1972. It specifies the minimum requirements for seat strength and strength of the interface between a seat and a vehicle. Section 4.2(d) requires that a seat withstand a 3,300 in-lbs (373 Nm)[(1)] moment applied at the upper cross-member of the seat back and measured about the H-point. The European seat standard, ECE No. 17, requires the same seat back strength test procedure with a performance value of 4,691 in-lbs (530 Nm).

Since 1989 the National Highway Traffic Safety Administration (NHTSA) has granted three petitions related to seating system performance. Petitions from Saczalski (July 1989) [1] and Cantor (February 1990) [2] are still open. The Saczalski petition seeks an increase in the requirement of S4.2(d) from 3,300 in-lbs (373 Nm) to 56,000 in-lbs (6,327 Nm) to reduce the frequency of seat back failures in rear impacts. The petitioner believes this is achievable with state-of-the-art materials and design techniques. Similarly, the Cantor petition asks that the standard be revised to prohibit the relative motion between the occupant and the seat back (ramping) due to seat back failure. In November of 1992 the agency published a Request for Comment notice [3] on recent research findings and a proposed research plan. The agency stated that improving seating system performance may be more complex than simply increasing the strength of the seat back. A proper balance in seat back strength and compatible interaction with head and belt restraints must be obtained to optimize injury mitigation. Therefore, the agency would refrain from action on upgrading FMVSS No. 207 until significant results from research were obtained. Commenters supported the research plan, but had disparate opinions on seating safety issues.

As part of this research the agency has performed its own research and funded a project by outside contractors. One of these outside contracts was at the University of Virginia (UVA). UVA developed a computer model of a production seat (1986 - 1994 Pontiac Grand Am) to study the safety issues related to rear impacts. Three associated reports were placed in the NHTSA docket (89-20-No.3) and recently transferred into the Department of Transportation docket system (NHTSA-1998-4064-24) [4]. UVA concluded that increasing the seat back resistance to rotation by about three times the baseline modeled seat improves the simulation results with respect to seat back rotation and subsequent occupant ramping.

There is a currently ongoing NHTSA funded research project which is an attempt at developing an advanced integrated safety seat which exceeds current FMVSS requirements. The contractor is EASi Engineering. A final report on the design of the seat was recently placed in the DOT docket (NHTSA-1998-4064) [5]. Building and testing of the prototype is planned for the next phase of the project. The design includes a plastically deforming seat back to absorb energy and reduce rebound in a rear impact.

The goal of the project reported here is to assess the rearward strength characteristics of a large number of current seat designs with respect to FMVSS 207.

2. Test Procedure

The moment versus angular deflection of original equipment manufacturer (OEM) seats was measured using the test procedures defined by SAE J879, Section 4.2. In this procedure the force (F_N) is applied about the H-point (SAE J826), normal to the torso line (SAE J383), at the seat back upper crossmember (fig.1). The actual loading device used was the head form defined in FMVSS 202 S5.2(c) connected to a loading arm which rotated about the H-point (fig. 2). The initial torso line angle with respect to the vertical is phi_I The loading arm rotational displacement was controlled such that the nominal displacement rate was 2 deg./s. The rotational displacement was released at the same rate as applied. The moment (F_NxD) about the H-point gave a measure of the seat back resistance to the applied displacement.

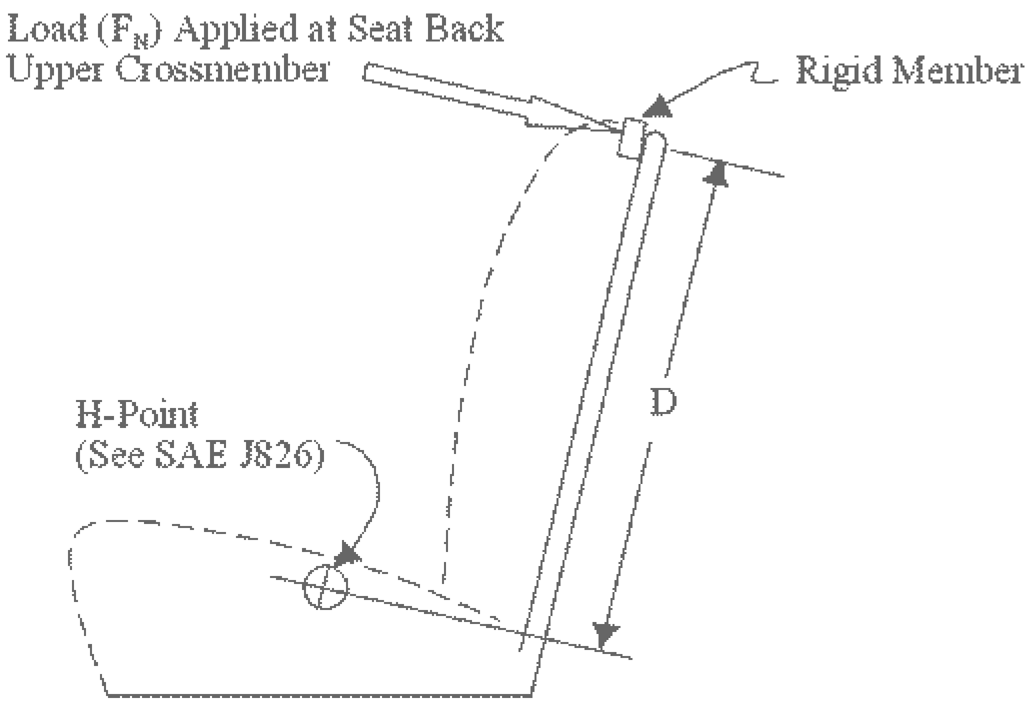

Figure 1 - Force at upper crossmember creates moment (F_NxD) about the H-point.

The seat was installed on a jig simulating the vehicle floor with the seat placed in its rearmost position. The initial seat back angle was its normal driving position as defined by the OEM and determined from the torso line of the three dimensional H-point manikin (SAE J826). The torso line angle was 22 degrees from the vertical for all seats except one. The moment and deflection data were acquired at a rate of 100 Hz during both the load application and release phases. The applied moment was calculated to an accuracy of ± 1%. Angular measurement was accurate to within ± 0.5 degrees.

In designing the loading arm, the goal was to have the initial applied load perpendicular to the torso line. If this were the case the force perpendicular to the torso line would simply be the measured load (F_M) and the moment about the H-point generated by this load would be F_M multiplied by the length of the load arm long axis (L). Because of differences in seat design it was not always possible to have F_M perpendicular to the torso line. This made it necessary to correct for the actual direction of applied load when calculating the moment about the H-point.

In making this moment correction certain assumptions were made. It was assumed that the normal vector of the seat structure at the point of contact with the head form was perpendicular to the torso line. Further, the frictional component of the applied load was ignored so that only a normal force was applied to the seat structure. Therefore, the measured load (F_M) was a component of the normal load in the direction of the load cell. Finally, it was assumed the point of contact on the head form was along the axis passing through the center of the load cell and head form.

A further refinement of the correction factor would have been to consider friction at the point of contact with the seat structure and to not make any assumption about the normal vector of the seat back structure. Assuming static friction and therefore no relative movement between the head form and seat, this would have resulted in a difference in final calculated moments of at most 2-3% from the moments calculated in this report. However, almost immediately after loading is applied relative motion occurs, resulting in dynamic friction. Accounting for dynamic friction would be very difficult and would change the calculated moment by a negligible amount.

Figure 3 shows the test setup geometry in detail. The torso reference line (line with dimension D) and the long axis of the loading arm (line with dimension L) have angular orientations which differ by the angle Theta. Thus, the force measured by the load (F_M) has the following relationship to the force normal to the torso line (F_N).

$$F_N = F_M/\cos(\text{Theta}) \tag{1}$$

The moment about the H-point generated by this Normal force is given by eq. (2).

$$M_H = F_N \bullet D \tag{2}$$

From the geometry shown in Figure 3 eqs. (3) and (4) can be derived.

$$D + B = L \cos(\text{Theta}) \tag{3}$$
$$B = A \sin(\text{Theta}) \tag{4}$$

Substituting eq.(4) into eq.(3) results in eq.(5)

$$D = L \cos(\text{Theta}) - A \sin(\text{Theta}) \tag{5}$$

Finally, substitutions of eqs.(5) and (1) into eq.(2) results in corrected moment represented by eq.(6).

$$M_H = F_M (L - A \tan(\text{Theta})) \tag{6}$$

Because the long axis of the loading arm and the torso line usually only varied by a few degrees the correction was relatively minor with M_H varying from $F_M \bullet L$ by only a few percent.

For most seats tested there was a driver and passenger version from the same vehicle which were of the same structural design except for the recliner mechanism being on the opposite side of the seat. For one of the seats the loading arm was rotated through an angle exceeding 70 degrees resulting in the seat back being in a nominally horizontal position. For the other seat the loading arm was not rotated as far in order to determine the energy stored in the seat when not completely collapsed. The goal was to rotate the seat to a point below its ultimate strength, but beyond its yield point. This was achieved by setting the maximum loading arm rotation for a twin seat to approximately 75% of the angle at which the first seat had achieved its maximum moment value. For several of the seat designs this rotational angle was not achieved for a variety of reasons.

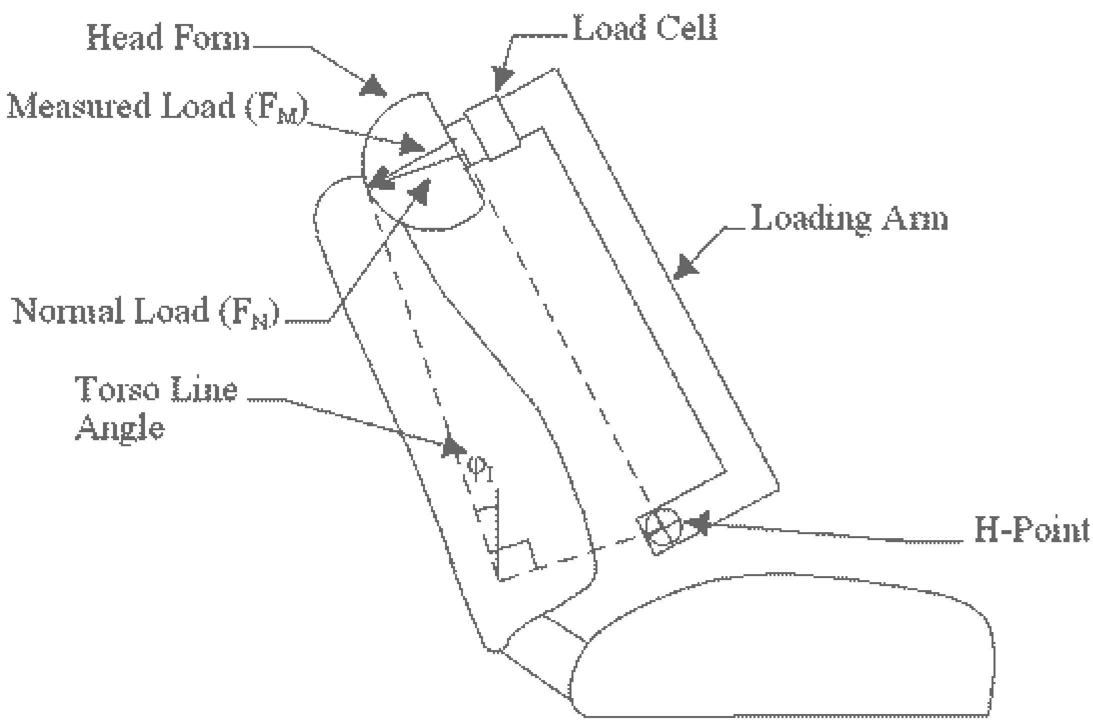

Figure 2 - Loading arm rotates about the H-point and applies force through head form.

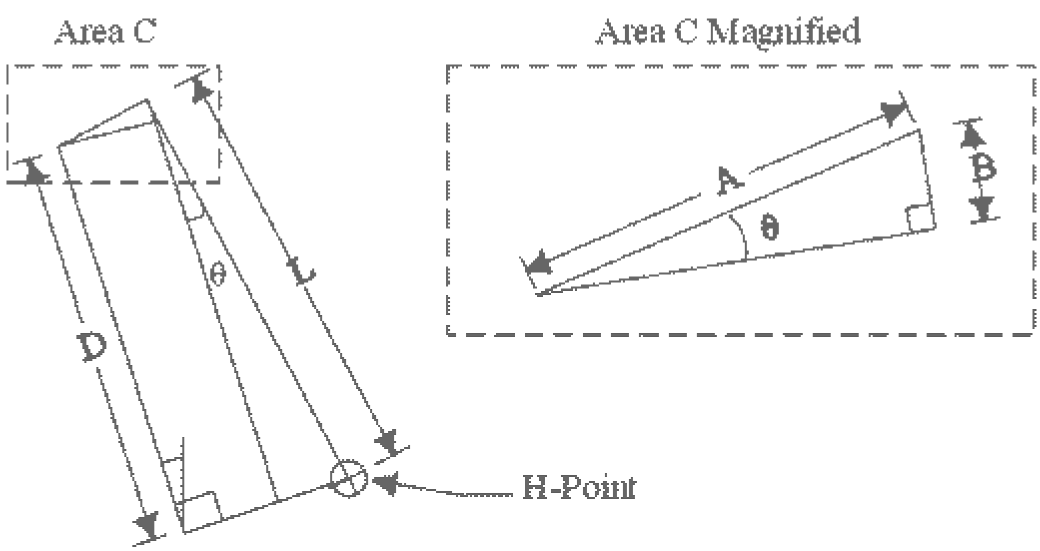

Figure 3 - Details of test set-up geometry.

Many of the seats tested (Table 1) were from vehicles previously compliance tested to specific FMVSS requirments. The seats were selected such that the previous tests did not have a significant affect on the seat structure. It was determined that the compliance tests were not likely to have affected the seats. The seats were taken from 24 different vehicles. There are, however, 25 unique seat designs because the Mazda had both a power and a manual recliner seat. Table 1 lists whether the seat has a dual or single recliner mechanism. Dual recliner seats have a locking recliner mechanism on both sides of the seat between the seat back and seat base. Single recliner seats are free to pivot at the attachment between the seat back and seat base on the inboard side of the seat. Table 1 also lists the seat back structural design as one of three options. These are tubular, stamped or hybrid. This assessment is somewhat subjective. Those listed as having a tubular structure where predominately constructed of round cross-section members bent to form the seat back (Figure 4). There was normally additional non-tubular structure at the connection to the recliner mechanism. Those designs designated as stamped were made of stamped or formed sheet metal spot welded together (Figure 5). Finally, the hybrid category was used for designs which showed significant amounts of both types of construction (Figure 6). This was exemplified by side vertical members with formed sheet metal structures welded to them and tied into the recliner structure.

Table 1 - Tested Seats

No. of Seats	Make	Model	Model Yr	Recliner	Structure
1	Chevrolet	Astro Van	1996	Single	Tubular
2	Chevrolet	Suburban	1996	Single	Tubular
2	Nissan	Quest	1995	Dual	Hybrid
2	Ford	Windstar	1995	Single	Formed
2	Dodge	B250 Van	1996	Dual*	Tubular
2	Saab	900S	1996	Dual	Formed
2	Ford	Contour	1995	Dual	Formed
2	Hyundai	Sonata	1995	Single	Tubular
2	Hyundai	Accent	1996	Single	Tubular
2	Nissan	Sentra	1996	Dual	Hybrid
2	Ford	Explorer	1996	Single	Formed
4	Honda	Passport	1995	Single	Tubular
2	Dodge	Neon	1994	Single	Tubular
2	Dodge	Intrepid	1996	Single	Tubular
2	Isuzu	Rodeo	1996	Single	Tubular
2	Chrysler	Cirrus	1996	Dual	Tubular
2	Ford	Taurus	1996	Single	Tubular
2	Pontiac	Sunfire	1996	Single	Tubular
2	Chevrolet	Blazer	1995	Single	Tubular
2	Mazda	Protégé	1995	Single	Tubular
2	Toyota	4-Runner	1996	Dual	Hybrid
1	Nissan	Maxima	1995	Dual†	Hybrid

2	Mazda	Millenia	1995	Dual	Hybrid
2	Chevrolet	T-600	1996	Single	Tubular

*Seat fixed on both sides. † Power and Manual Recliner Designs.

Figure 4 - Sunfire tubular seat back structure.

Figure 5 - Windstar stamped seat back structure

Figure 6 - Maxima hybrid seat back structure.

3. Computational Methods

The rotation displacement of the loading arm vs. the applied moment was plotted for each tested seat. The plots are contained in Appendix A. For each plot the range of data which generates the coefficient of correlation (R^2) closest to one was calculated. An $R^2 = 1$ indicates a perfect linear fit to the data. The identified data range was, therefore, the most linear portion of the moment-displacement curve. The algorithm for identifying the linear range of data is shown in Appendix B. The premise was to take the first 50 data points (approximately 1 degree of loading arm rotation) and calculate R^2. Next the value of R^2 was calculated for data points 2 through 51. If this R^2 was larger than the first it was stored. The 50 data point window was moved through the entire data set and the value of R^2 closes to one determined. Next, the number of data points in the window was increased by 1 and the largest R^2 was determined and compared to the largest from the previous window size. The process was completed when the data point window encompassed the entire data set. Once the most linear window of data was determined, an equation for the best fit line through that data was calculated as represented below. The parameters S and b represent the slope and intercept of the best fit line. S is a measure of seat back stiffness and has the units of in-lbs/deg.

$$M_{HL} = S \bullet phi + b \tag{7}$$

M_{HL} = Predicted linear portion of applied moment

S = Seat back stiffness

phi = Load arm angle normalized to initial torso line angle

For the purposes of this study the yield strength of the seat back was determined by calculating the difference between the predicted linear moment (M_{HL}) and the measured applied moment (M_H). When the value of M_H is such that eq.(8) is true, the yield strength has been reached. This will be referred to as the yield or 5% yield interchangeably.

$$(M_{HL} - M_H)/M_H \ 5\% \tag{8}$$

The amount of work (W) done on the seat back is represented by the area under the moment-rotational displacement curve as the loading arm angle increases (fig.7). Similarly, the energy returned (E) by the seat back is represented by the area under the moment-rotational displacement curve as the loading arm angle decreases (fig. 8). The energy return is a negative quantity. Both of these parameters have units of inch-pounds or Newton-meters. The energy dissipated by the seat is the sum of W and E.

Nissan Quest

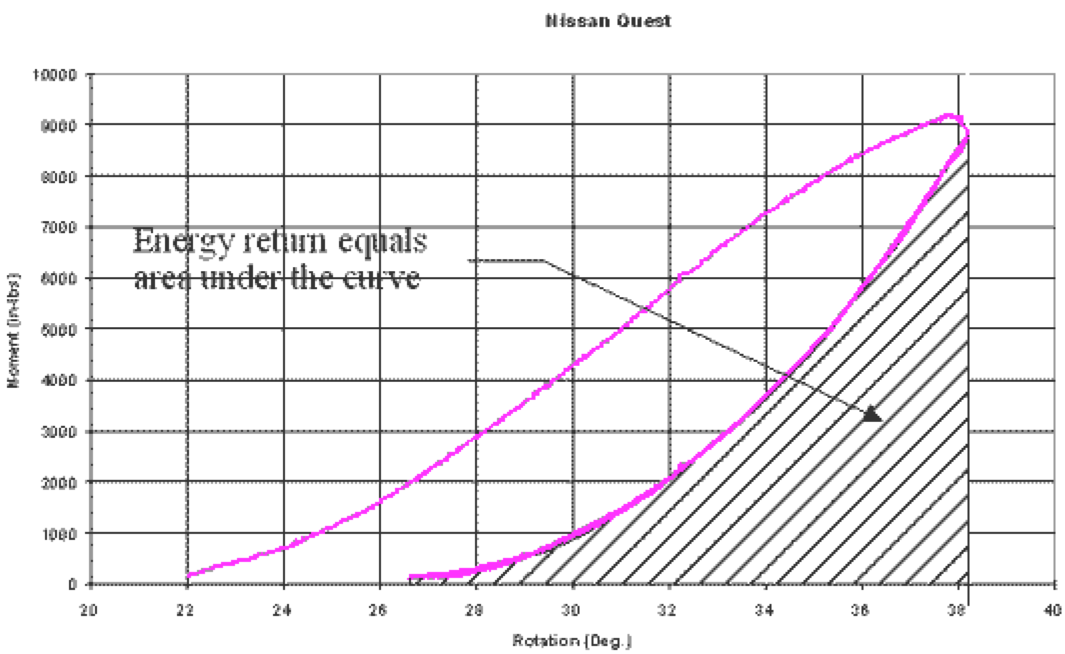

Figure 8

4. Quantitative Results

During the data reduction process the data from two symmetric seat designs for a single vehicle was combined to represent the results for that seat design. Although the results from 48 seat tests were analyzed, these represent 25 unique seat designs. The reader is referred to Appendix C for data from each of the 48 individual tests. For each seat design the average yield strength and ultimate strength were determined (Table 2). The ultimate strength is represented by the maximum moment resisted by the seat back. Table 2 shows the loading arm rotation from its initial position and the work performed at the 5% yield and ultimate strength values. On average, yield occurred at 6,814 in-lbs (770 Nm) after 15.8 degrees of load arm rotation. The average ultimate strength value was 11,266 in-lbs (1,273 Nm) at 35.6 degrees of load arm rotation. Table 3 segregates the data by recliner design. The moments at yield and ultimate strength were 37% greater for dual recliner than single recliner seats. These moments were achieved after smaller amounts of loading arm rotation. Both recliner designs had similar amounts of work done on them at yield. Dual recliner seats had 19% more work done on them at ultimate strength. Figures 9 and 10 show the moment value and energy input at the 5% yield point. Figures 11 and 12 show the same parameters at ultimate strength.

Table 2 - Average Moment and Work (± Std Dev.) at 5% Yield and Ultimate Strength for All Seats

Strength	Arm Rotation (deg.)	Moment (in-lbs)	Work (in-lbs)	n
Yield	15.8 ±5.2	6814 ±1878	910 ±413	25
Ultimate	35.6 ±9.64	11266 ±3275	4161 ±1854	25

Table 3 - Average Moment and Work (± Std Dev.) at 5% Yield and Ultimate Strength by Recliner Type. Units in deg. and in-lbs.

	Single Recliner				Dual Recliner			
	Rot.	**Mom.**	**Work**	**n**	**Rot.**	**Mom.**	**Work**	**n**
Yield	17.0 ±5.8	5945 ±1100	922 ±470	15	13.9 ±3.7	8118 ±2091	893 ±332	10
Ult.	37.5 ±8.0	9825 ±1523	3868 ±1320	15	32.7 ±11.5	13427 ±4043	4599 ±2470	10

Avg. Energy Input (+/-1 STD) at 5% Yield Strength

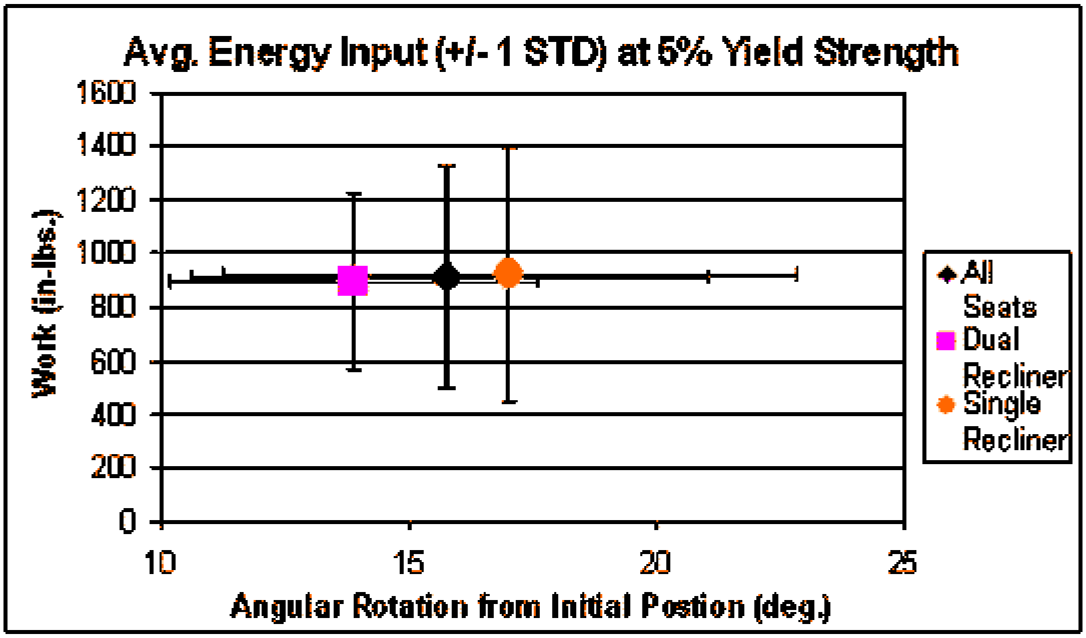

Figure 9

Avg. 5% Yield Strength (+/-1 STD) of Seat

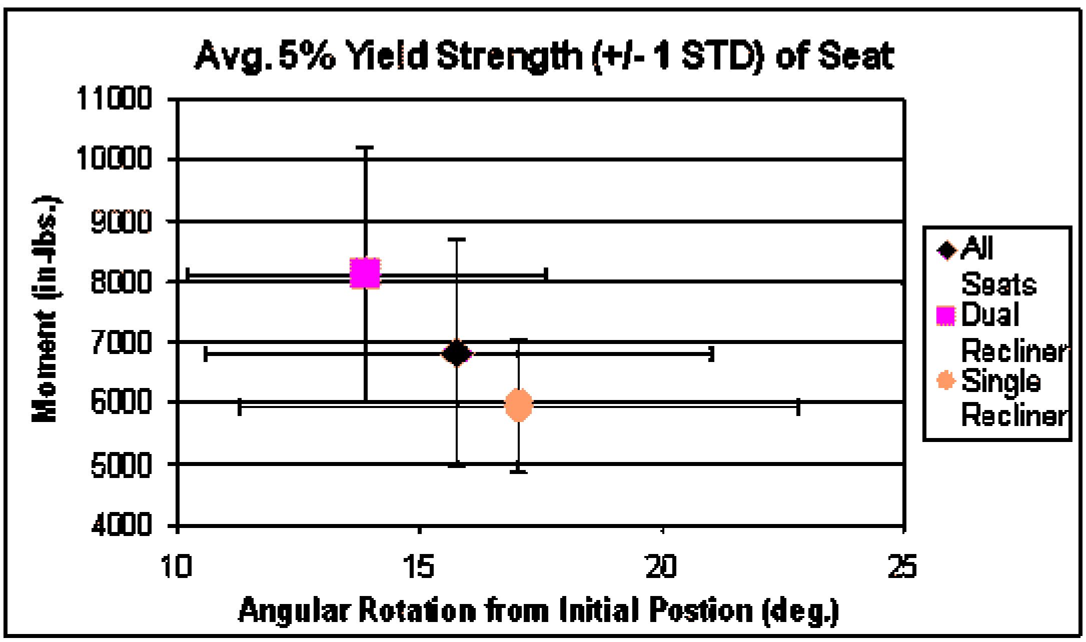

Figure 10

Avg. Ultimate Strength (+/-1 STD) of Seat

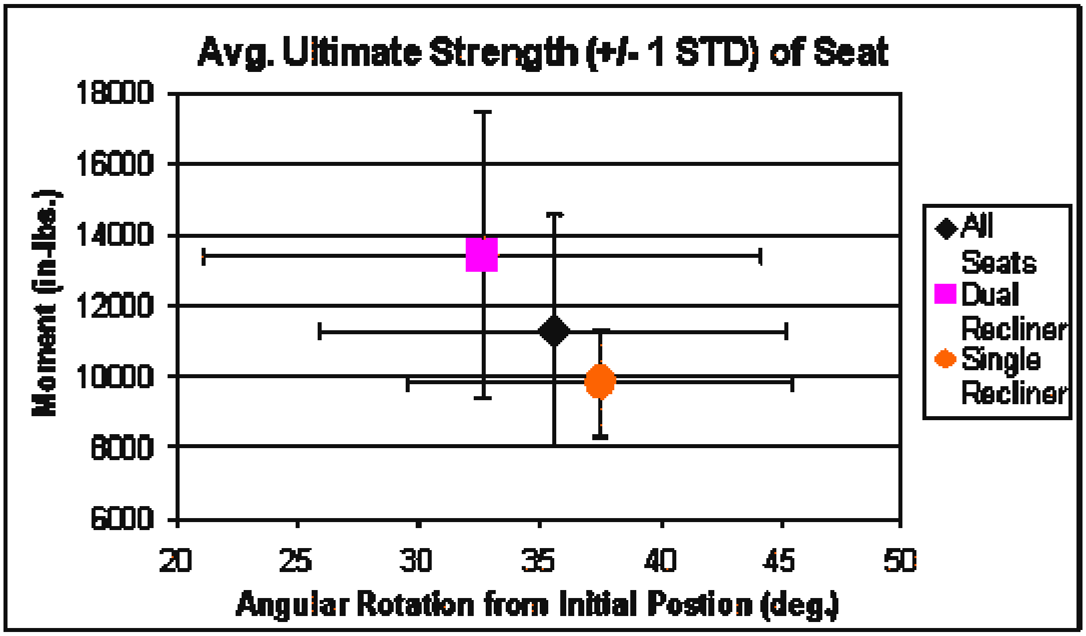

Figure 11

Avg. Energy Input (+/-1 STD) at Ultimate Strength

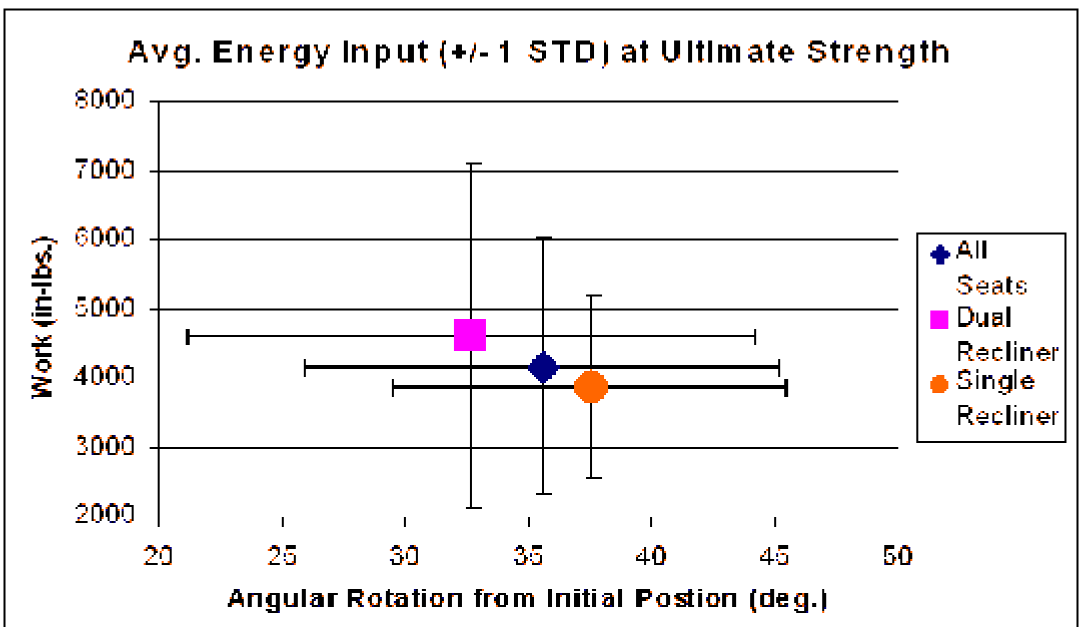

Figure 12

As shown in Table 4, the Saab 900S had the maximum ultimate strength (20,300 in-lbs (2,294 Nm)). The seat that exhibited the minimum ultimate strength was the Chevrolet Suburban (7,290 in-lbs (824 Nm)). The seat which had the most work input when the ultimate strength was achieved was the Mazda Millenia power recline seat (9,830 in-lbs (1,111 Nm)). The Toyota 4-Runner sustained 1,499 in-lbs (169 Nm) of work at ultimate strength which was the minimum for any seat tested.

Table 5 lists the seats which had the maximum and minimum 5% yield strength and the seats which had the maximum and minimum amount of work done on them at the 5% yield point. It must be noted that the yield point is a very sensitive parameter. A slight change to the equation fit to the linear portion of the moment-deflection curve or any perturbation in the curve itself may alter the yield point significantly. The Saab 900S had a moment value of 11,863 in-lbs (1,340 Nm) at yield, which was the largest of all seats. The Isuzu Rodeo had the smallest moment value at yield (4,185 in-lbs (473 Nm)). The Chevrolet T-600 had 1,974 in-lbs (223 Nm) of work done on it at yield which was the most of any seat. The Mazda Millenia had the least amount of work done at yield (312 in-lbs (35 Nm)). From Figure A24 in Appendix A, this appeared to be caused by an abrupt, yet small, drop in the moment value at approximately 28 degrees of loading arm rotation.

Table 4 - Vehicle Seats with Maximum and Minimum Moment and Work Values at Ultimate Strength. Units of deg. and in-lbs.

Vehicle	Rotation	Mom. (Max./Min.)	Work (Max./Min.)	Recliner Type	Appendix A Fig. Ref.
900S	32.6	(20,300)	6,372	Dual	A6
Suburban	32.9	(7,290)	2,731	Single	A2
Millenia*	50.0	18,759	(9,830)	Dual	A24
4-Runner	40.2	10,658	(1,499)	Dual	A22

*Power Recline Driver Seat

Table 5 - Vehicle Seats with Maximum and Minimum Moment and Work Values at 5% Yield Strength. Units of deg. and in-lbs.

Vehicle	Rotation	Mom. (Max./Min.)	Work (Max./Min.)	Recliner Type	Appendix A Fig. Ref.
900S	39.4	(11,863)	1,533	Dual	A6
Rodeo	32.3	(4,185)	341	Single	A16
T-600	48.5	7,420	(1,974)	Single	A25
Millenia*	28.5	5,987	(312)	Dual	A24

*Manual Recline Passenger Seat

Table 6 shows the average moment and work values at 10 degree increments of loading arm rotation. The average for all seats is given as well as for data segregated by single and dual recliner designs. The moment and work values at each 10 degree increment are greater for the dual recliner seats. The average moment value peaks at around 30 degrees of loading arm rotation. At 30 degrees the dual recliner seat average moment value is 32% greater than the single recliner seat value. Figures 13 and 14 is a graphical representation of this data.

Table 6 - Average Moment and Work (± Std Dev.) at 10 Degree Increments of Loading Arm Rotation. Units of deg. and in-lbs.

	All Seats			Single Recliner			Dual Recliner		
Rotation	**Mom.**	**Work**	**n**	**Mom.**	**Work**	**n**	**Mom.**	**Work**	**n**
10	4491 ±1881	352 ±152	25	3542 ±886	283 ±81	15	5915 ±2113	455 ±177	10
20	8317 ±2753	1502 ±563	25	6880 ±1318	1207 ±256	15	10472 ±2985	1945 ±617	10
30	9913 ±3238	3099 ±1031	24	8839 ±1174	2633 ±431	15	11703 ±4687	3877 ±1280	9
40	9565 ±2914	4816 ±1513	24	8662 ±1494	4174 ±587	15	11068 ±4055	5887 ±1978	9
50	9011 ±3260	6411 ±1894	24	8258 ±1949	5646 ±746	15	10267 ±4590	7688 ±2530	9

Average H-Point Moment

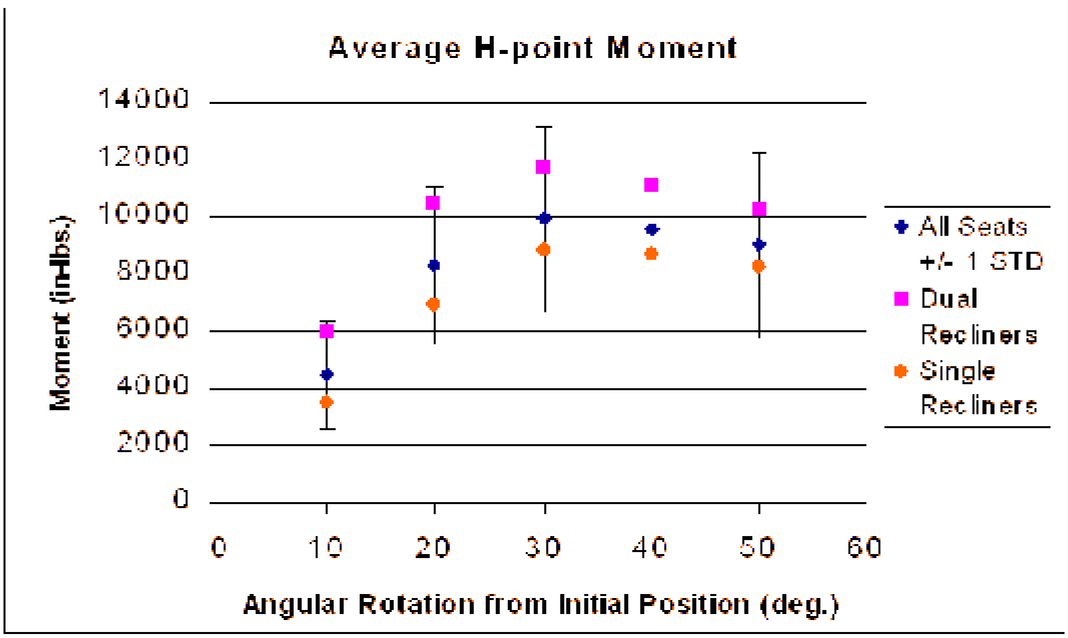

Figure 13

Average Input Energy to Seat

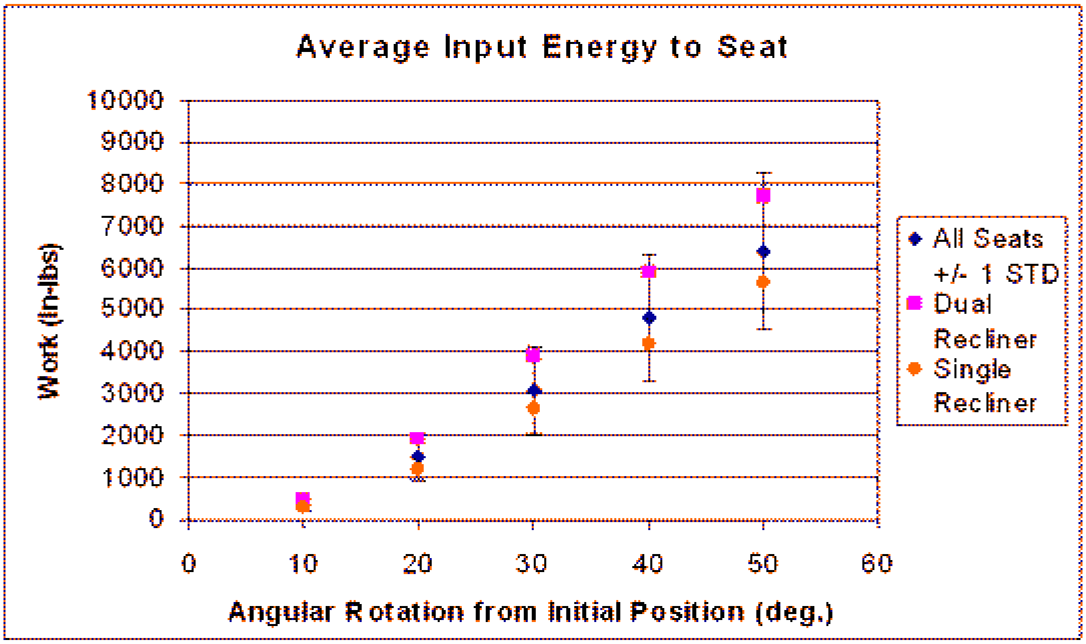

Figure 14

FMVSS 207 requires that a seat back sustain a 3,300 in-lb (373 Nm) moment with respect to the H-point. Figure 15 shows the average amount of loading arm rotation at 3,300 in-lbs (373 Nm) of applied moment. The average loading arm rotation for all seats was 8.7 degrees. For single and dual recliner seats the rotation was 9.8 and 7.1 degrees, respectively. The values in Table 3 indicated that 5% yield at 14 and 17 degrees for single and dual recliner seats. Thus, in general, seat backs are still in a linear deflection regime when achieving the 3,300 in-lb (373 Nm) moment. The smaller amount of rotation allowed by dual recliner seats indicates a greater stiffness. The average seat back stiffness about the H-point as determined by eq.(7) by seat type is given in Table 7. Dual recliner seats show a 77% greater stiffness than single recliner seats. The seat with the greatest stiffness is the Mazda Millenia manual recline seat (Table 8). The smallest stiffness is exhibited by the GM Astro seat.

Rotation at FMVSS 207 Moment Limit (3,300 in-lbs.)

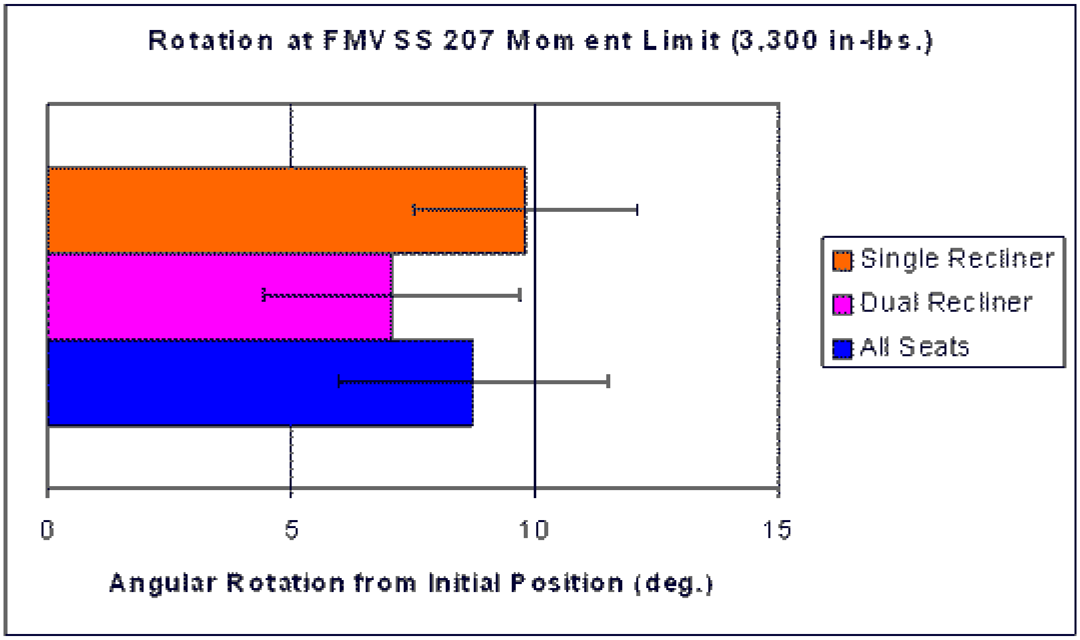

Figure 15

	Stiffness (in-lbs/deg.)	n
All Seats	576 ±249	25
Single Recliners	434 ±121	15
Dual Recliners	789 ±238	10

Table 8 - Vehicle Seats at Extremes of Seat Back Stiffness

	Vehicle	Stiffness (in-lbs/deg.)	Recliner Type	Appendix A Fig. Ref.
Maximum Stiff.	Mazda Millenia*	1,191	Dual	A24
Minimum Stiff.	GM Astro	216	Single	A1

*Manual Recline Passenger Seat

As stated in Section 3, an attempt was made to determine the work input, energy return and energy dissipated for each seat design by displacing the loading arm to 75% of the rotation which achieved the ultimate strength of a previously tested seat of the same design. If the loading arm rotation ratio for a seat design was between 0.70 - 0.76 it was used in this analysis (Table 9). Figures 7 and 8 graphically depicts the work input and energy return of a tested seat. For single recliner seats the Accent returned the most energy (-986 in-lbs (-111 Nm)). It also had the most work input (3,737 in-lbs (422 Nm)). For the dual recliner seats the Saab 900S had the largest work input (2,881 in-lbs (325 Nm)) and energy return (-1,173 in-lbs (-133 Nm)). This suggests some relationship between the work input and energy return of a seat. Figure 16 is a plot of work vs. energy return for each recliner type. The equation for the best fit lines and correlation coefficients (R^2) are shown in the figure. An $R^2 = 1$ is a perfect linear fit. The correlation coefficients for single and dual recliner seats were $R^2 = 0.80$ and 0.98, respectively. This indicates a good correlation, especially for dual recliner designs. However, the dual recliner correlation is only based on four points. When both dual and single recliner data are used the $R^2 = 0.75$.

The relationship between work input and energy dissipated was also examined. Again the correlation is best when dual and single recliners are separated. The correlation coefficients for single and dual recliner seats were $R^2 = 0.98$ and 0.99, respectively. When the data are grouped the correlation remains high at $R^2 = 0.97$. Figure 17 shows a plot of work input vs. energy dissipated.

Table 9 - Work Input (in-lbs), Energy Return (in-lbs) and Energy Dissipated (in-lbs) for Seats with Loading Arm Rotation Ratio of between 0.70 and 0.76.

Vehicle	Work Input	Energy Return	Energy Dissipated	Loading Arm Rot. Ratio	Recliner Type	Appendix A Fig. Ref.
Suburban	1121	-316	805	.73	Single	A2
Sonata	2636	-914	1722	.76	Single	A8
Accent	3737	-986	2751	.76	Single	A9
Passport	1636	-609	1027	.70	Single	A12 - 13
Neon	1312	-505	806	.73	Single	A14
Intrepid	1244	-381	863	.73	Single	A15
Rodeo	1163	-457	706	.75	Single	A16
Taurus	1570	-758	812	.70	Single	A18
T-600	3186	-851	2335	.75	Single	A25
Quest	1272	-610	662	.75	Dual	A3
900S	2881	-1173	1707	.74	Dual	A6
Cirrus	1615	-643	972	.75	Dual	A17
4-Runner	1220	-494	726	.75	Dual	A22

Relationship between Work Input and Energy Return

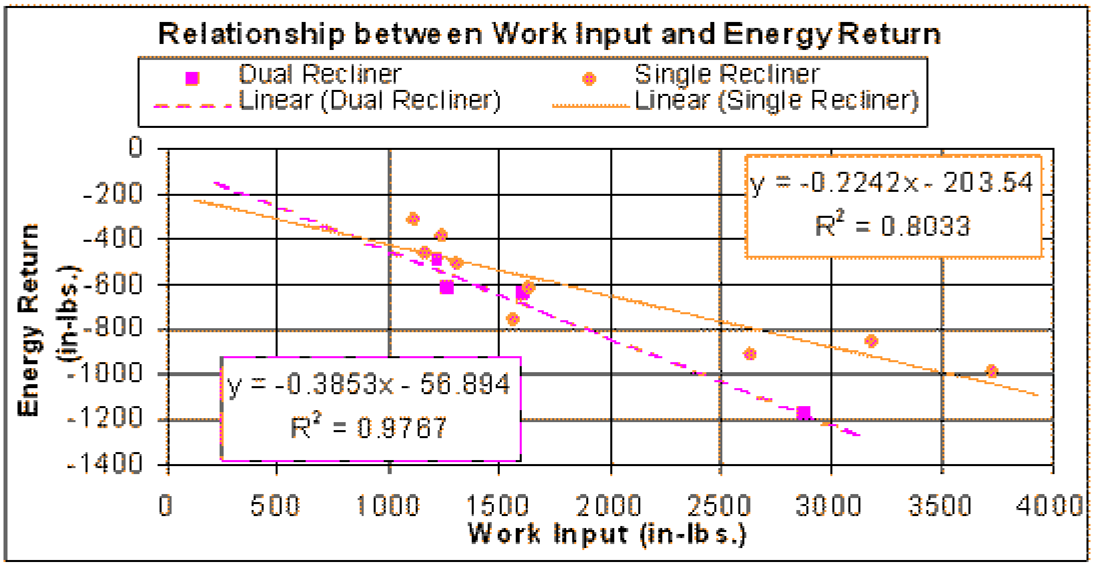

Figure 16

Relationship between Work Input and Energy Dissipated
Dual and Single Recliner Designs

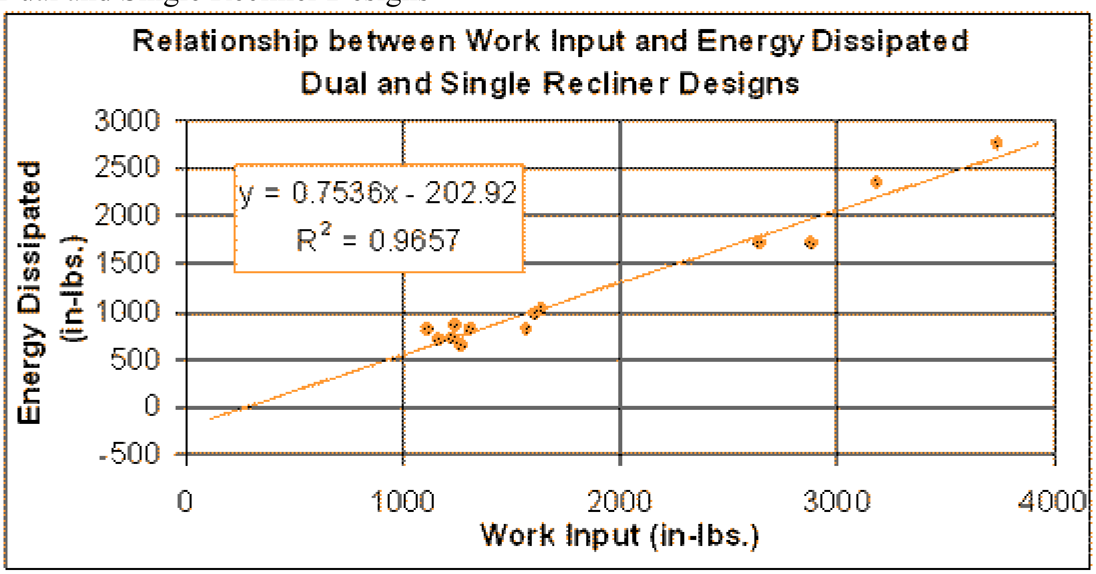

Figure 17

5. Qualitative Results

Figures 18-20 show the load application sequence for the Suburban driver seat. This seat has a single recliner on the outboard side and a free pivot on the inboard side. This seat had the lowest ultimate strength of any tested (7,290 in-lbs (824 Nm)). Twisting of the seat is evident such that the inboard side deflects to a greater extent than the outboard side. This was typical for single recliner seats. Figure 21 shows the recliner and a portion of the seat back structure with the seat back upholstery removed. The seat back structure is composed of welded tubular members fastened to the recliner mechanism. The seat back structure is clearly deformed rearward where it attaches above the recline mechanism, but the recliner seems to have remained engaged. This was the typical failure mode. However, some models showed additional deformation in the recliner hardware. Figure 22 shows the recliner mechanism from the Suburban passenger seat. This seat was loaded such that the maximum loading arm rotation was 24 degrees from its initial position. The recliner and seat back structure do not show the extreme deformation evident in the driver seat.

Figure 23 shows the Saab 900S passenger seat, post-test, with the seat back upholstery removed. In addition to having dual recliners, the seat back structure is made of stamped members as opposed to the tubular design of the Suburban. This seat sustained the highest moment (20,300 in-lbs (2,294 Nm)) of all tested seats. The seat back evidently deformed uniformly without twisting. This was generally the case for the dual recliner seat designs tested. Figures 24 and 25 show both recliners of the 900S passenger seat. It appears that both mechanisms remained engaged, but deformed considerably. The seat back members on both sides twisted out of their original plane, but the plane of the seat back itself did not twist significantly to one side or the other. Figures 26 and 27 show the Saab 900S drivers seat. This seat was loaded such that the maximum loading arm rotation was 24 degrees from its initial position. The recliner and seat back structure do not show the extreme deformation evident in the passenger seat.

Although the typical failure mode for seat backs appeared to be plastic deformation of the members attached to the recliner, several force deflection curves show a rapid moment decrease of 500 - 1,000 in-lbs (56 - 113 Nm) followed by a steady increase in moment. This is visible in the graphs for the Windstar, Passport, Rodeo, Sunfire, Protégé and 4-Runner. The graph of the Explorer shows a complete and instantaneous moment lose, indicating a lack of resistance at the recliner. All of these seats have single recliners except the 4-Runner. This is consistent with failure of teeth in the recliner. The recliners were not disassembled to verify this hypothesis.


Figure 19


Figure 20


Figure 21

Figure 22


Figure 23


Figure 24

Figure 25

Figure 26

Figure 27

6.1 Comparison to Previous Research

6.1.1 Static Analysis

As mentioned in the Introduction, UVA developed a computer seat model based on a production General Motors single recliner seat used for many years beginning in 1986 [4]. This model had a seat back stiffness about the H-point of 375 in-lbs/deg (42 Nm/deg) and an ultimate strength of 8,625 in-lbs (974 Nm) occurring at 36 degrees of seat back deflection. This stiffness and ultimate strength are 14% and 12% less, respectively, than the average for single recliner seats reported here.

Research was performed by Stother et al. in the past to evaluate the static seat back strength of seats in comparison to the FMVSS 207 requirements [6,7]. However, comparison of these results with the current testing is confounded by differences in test procedure. The procedure used by Stother was to place a body block in the seat and pull rearward on it at 14 inches above the H-point. This continued until the seat back reached 45 degrees of inclination. It is assumed for this comparison that the 45 degrees was referenced from initial seat back position. Vertical tension members were attached to the load application device to prevent ramping of the body block. Therefore, it is further assumed that the moment arm of the applied load was reduced, as the seat back rotated, by a factor of cosine of the angle of rotation. The force and energy absorbed by the seat at the 45 degree limit were calculated as well as the initial stiffness of the seat back.

The seats tested by Stother ranged from the 1964 to the 1988 model year. The average force measured at 45 degrees of rotation was 660.2 lbs (2,937 N). Converting this to applied moment by multiplying by 9.9 inches (14 cos 45) yields a moment about the H-point of 6,536 in-lbs (738 Nm). Interpolating between 40 and 50 degrees in Table 6 yields a moment value for all seats tested of 9,288 in-lbs (1,049 Nm) at 45 degrees in the current testing. For single recliner seats the 45 degree moment is estimated at 8,460 in-lbs (956 Nm) which is 23% greater than Stother. However, this is 45 degrees of loading arm rotation which may not mirror seat back rotation.

Stother calculated the absorbed energy at 45 degrees of seat back rotation to be 3,083 in-lbs (348 Nm). Interpolating the values in Table 6 again yields the work in the current project at 45 degrees of loading arm rotation to be 5,614 in-lbs (634 Nm) for all seats and 4,910 in-lbs (555 Nm) for single recliner seats. The Stother energy value is 37% less than in the current results for single recliners.

Finally, Stother calculated the seat back stiffness to be 134.8 lbs/in (23,610 N/m). This stiffness (S') is the slope of the equation for applied force (F) as a function of linear displacement (x) as represented by eq. 9.

$$F = S' \bullet x + b \tag{9}$$

In order to compare S' to the slope (S) calculated in the current testing and defined in eq. 7, eq. 9 is first multiplied by the moment arm value of 14 inches. Since only the slope values are of interest the intercept values are ignored and the result is the following.

$$S \bullet \text{phi} = 14\, S' \bullet x \tag{10}$$

For small angles,

$$x = 14\, \text{Theta}(\text{pi}/180) \tag{11}$$

where Theta is the seat back rotation in degrees and 14 inches the radius of the rotation. Assuming the seat back rotation in the Stother work mirrors the loading arm rotation in the current work, Theta = phi and eq. 12 can be developed.

$$S = S'(14)^2\, (\text{pi}/180) = 3.42\, S' \tag{12}$$

By using eq. 12, the average stiffness calculated from the Stother work is 461 in-lbs/deg (52 Nm/deg). The average stiffness measured in the current project is 576 in-lbs/deg (65 Nm/deg) for all seats and 434 in-lbs/deg (49 Nm/deg) for single recliner seats. The single recliner stiffness of the current work is 6% less than the estimate from Stother.

It is not known what seats if any tested by Stother et al. were dual recliner. There is a better match between the results of this previous work and the single recliner values measured in the current work. Still there are differences of 22% and 37% for the moment and energy calculations, but only 6% for stiffness. It is unknown if these differences are due to the dissimilar test procedures, the assumptions made to facilitate comparison of the results, or changes to seat designs. If the last possibility is correct it implies that seats have gotten stronger and more energy absorbent. If dual recliner designs are also considered, overall seat stiffness has also increased.

6.1.2 Dynamic Analysis

Previous research has indicated that seat back strength as described by stiffness and ultimate strength may, by itself or by interaction with other seat characteristics, strongly influence the injury reducing potential of seats in rear impacts. However, there seem to be differing opinions on whether this injury reducing potential is increased or decreased by making seat backs stronger. A French study of field data indicated that if a seat back breaks upon impact the need for head restraints is reduced because it may not become involved in altering occupant kinematics [8]. A recent NHTSA study using the National Automotive Sampling System (NASS) Crashwothiness Data System (CDS) showed that when a seat maintained its initial upright position after a rear impact, instead of ending up in a reclined position, the rate of whiplash injury increased [9]. However, the data also seemed to indicate that at up to an impact DeltaV of 25 mph the injury cost was less when a seat maintained its upright position. This was based on very limited data. Prasad et al. performed sled tests on seats of varying stiffness and concluded that stiffer seats don't have any consistent advantage over yielding seats over a broad range of impact velocities [10].

Using a seat computer model Nilson et al. evaluated a variety of seat back design parameters at a 20 mph DeltaV rear impact [11]. He showed that a seat with a stiffness of 1,540 in-lbs/deg (174 Nm/deg) with respect to the H-point had better neck injury reduction capability as measured by head to torso angle, head acceleration and upper neck moment as compared to seats with a 770 or 385 in-lbs/deg. (86 or 43 Nm/deg.) stiffness. He also showed that a seat with a stiffness of 770 in-lbs/deg (86 Nm/deg) with an ultimate strength of 13,300 in-lbs (1503 Nm) was sufficient to prevent the occupant from ramping out of the seat. This is consistent with the UVA study that concluded that increasing the seat back resistance to rotation by about three times the baseline modeled seat (1,125 in-lbs/deg (127 Nm/deg.) stiffness and ultimate strength of 25,875 in-lbs (2,923 Nm)) improves the simulation results with respect to seat back rotation and subsequent occupant ramping.

There are recent indications that approaches to seat design which address more than just seat back stiffness and ultimate strength may produce safety benefits. Volvo reported that they have developed a seat which utilizes a unique recliner design that may offer better protection against neck injury in rear impacts [12]. Upon impact the base of the seat back translates rearward and the head restraint moves towards the occupants head. The next phase of seat back motion is a rearward rotation incorporating energy absorption. The result was a reduction in peak lower neck accelerations in rear impacts up to a 12 mph (19.3 kph) DeltaV. The advanced seat design developed by EASi Engineering and funded by NHTSA incorporates similar design measures for energy absorption as the Volvo seat [5]. This was found in computer simulations to reduce the relative angle between the head and torso caused by seat rebound. The seat back is also designed to exhibit a maximum rotation of 30 degrees from its initial position when occupied by a 50th percentile male in a 20 mph (32.2 kph) DeltaV rear impact.

6.2 Current Work

The average yield strength and ultimate strength for all seats tested were 2.1 times and 3.4 times greater than the 3,300 in-lb (373 Nm) requirement of FMVSS 207. At 3,300 in-lbs (373 Nm) the average loading arm deflection was only 8.7 degrees. This indicates that the existing requirement is not motivating current seat back design.

Visual inspection of the seat frame, post-test, indicated that failure of the seat back structure typically occurred above the recliner mechanism with the mechanism itself remaining engaged. This is supported by the graphs of loading arm rotation vs applied moment. It is expected that failure of the recliner teeth would cause abrupt drops in the measured moment value. This was seen in a relatively small number of graphs (20%) and predominantly single recliners. For one of the Explorer seats tested the recliner failed completely, but at moment and work input values that exceeded the averages for single recliner seats.

There was a clear difference between the performance of dual and single recliner seats. The dual recliner seats were stiffer and stronger. The average moment at yield was 8,118 and 5,945 in-lbs (917 and 672 Nm) for dual and single recliner seats, respectively. The average ultimate strength was 13,427 and 9,825 in-lbs (1,517 and 1,110 Nm) for dual and single recliner seats, respectively. The average seat stiffness was 789 and 434 in-lbs/deg. (89 and 49 Nm/deg.) for dual and single recliner seats, respectively. The single recliner seats exhibited twisting to the non-recliner side of the seat back. This is expected because this side of the seat back can offer very little or no resistance to rotation.

The seat with highest ultimate strength was the dual recliner Saab 900S (20,300 in-lbs (2,294 Nm)). The lowest ultimate strength was the single recliner Suburban (7,290 in-lbs (824 Nm)). The seat that absorbed the most work input at ultimate strength was the dual recliner Millenia (9,830 in-lbs (1,111 Nm)). The seat that absorbed the least amount of work at ultimate strength was the dual recliner 4-Runner (1,499 in-lbs (169 Nm)). The stiffest seat was the Millenia (1,191 in-lbs/deg. (135 Nm/deg.)). The least stiff seat was the single recliner Astro (216 in-lbs/deg. (24 Nm/deg.)).

It was determined that a good correlation exists between the work input and energy return of the seat when the data are separated by recliner type. The more work input to a seat when the loading arm was rotated to 75% of ultimate strength, the more energy was returned from the seat. A better correlation exists between work input and energy dissipated by the seat. This correlation remains high when both single and dual recliner data are grouped. It is difficult to determine the implications of these correlation since they are derived at a single level of load arm displacement. To evaluate the energy dissipation inherent in an individual seat as a function of input work would require multiple tests at different levels of seat back displacement. This was not possible for the current evaluation.

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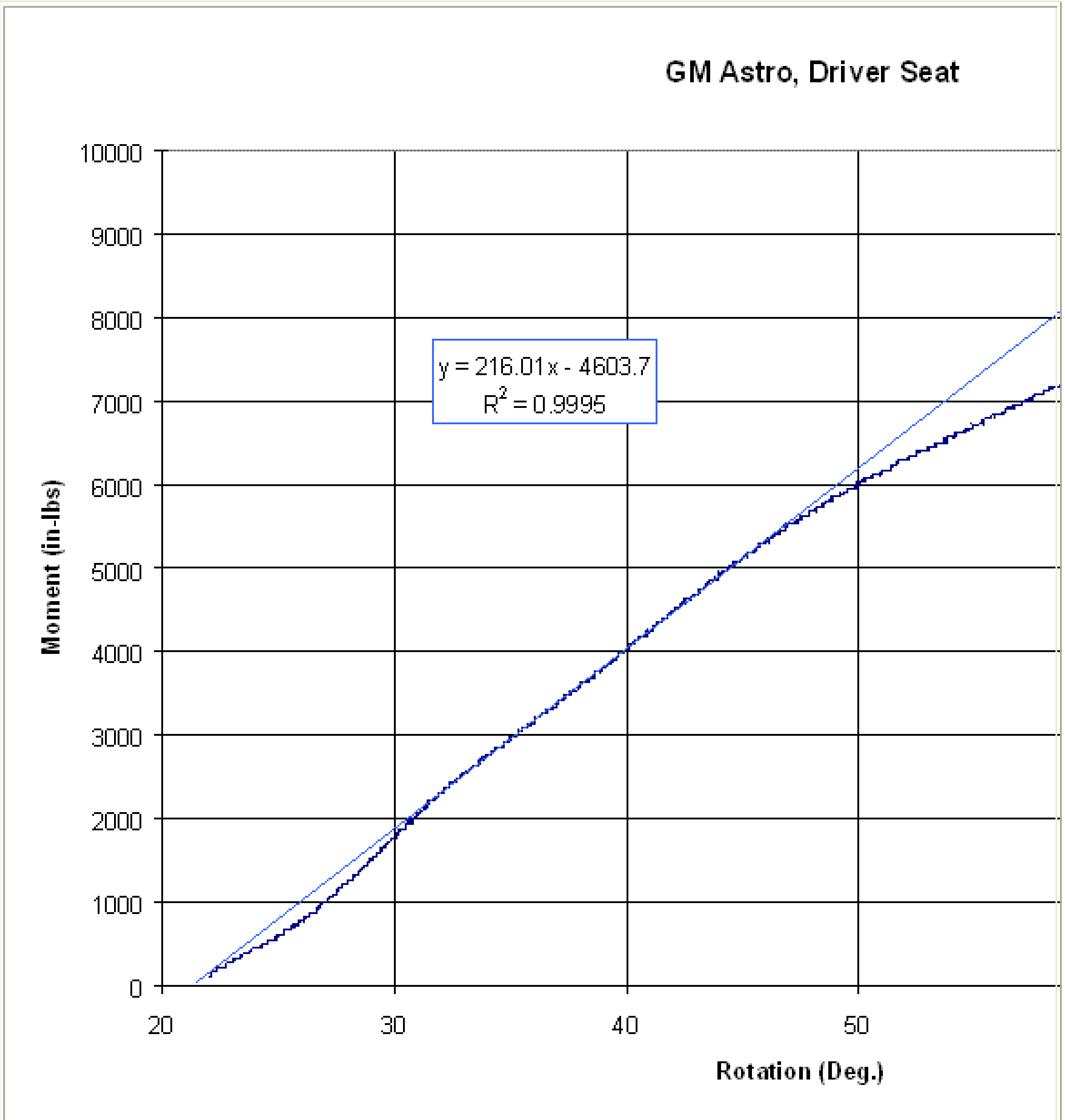
1. In the text numerical values will be given in English units and parenthetically in metric units. Graphs and table will be in English units only.

Appendix A

For the figures in this appendix, in general, the thinner lines represent the data from seats tested to failure and the thicker lines represent the data from seats deflected to approximately 75% of the ultimate load deflection. The straight lines represent the best fit through the data as determined by the method described in Section 3 and Appendix B. For the convenience of the reader, the key on each graph identifies the driver and passenger seat data. However, since the driver and passenger seats were symmetrical this was assumed to have no bearing on the results.


GM Astro, Driver Seat
y = 216.01x - 4603.7
R^2 = 0.9995
Moment (in-lbs)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
20
30
40
50
Rotation (Deg.)
Figure A1

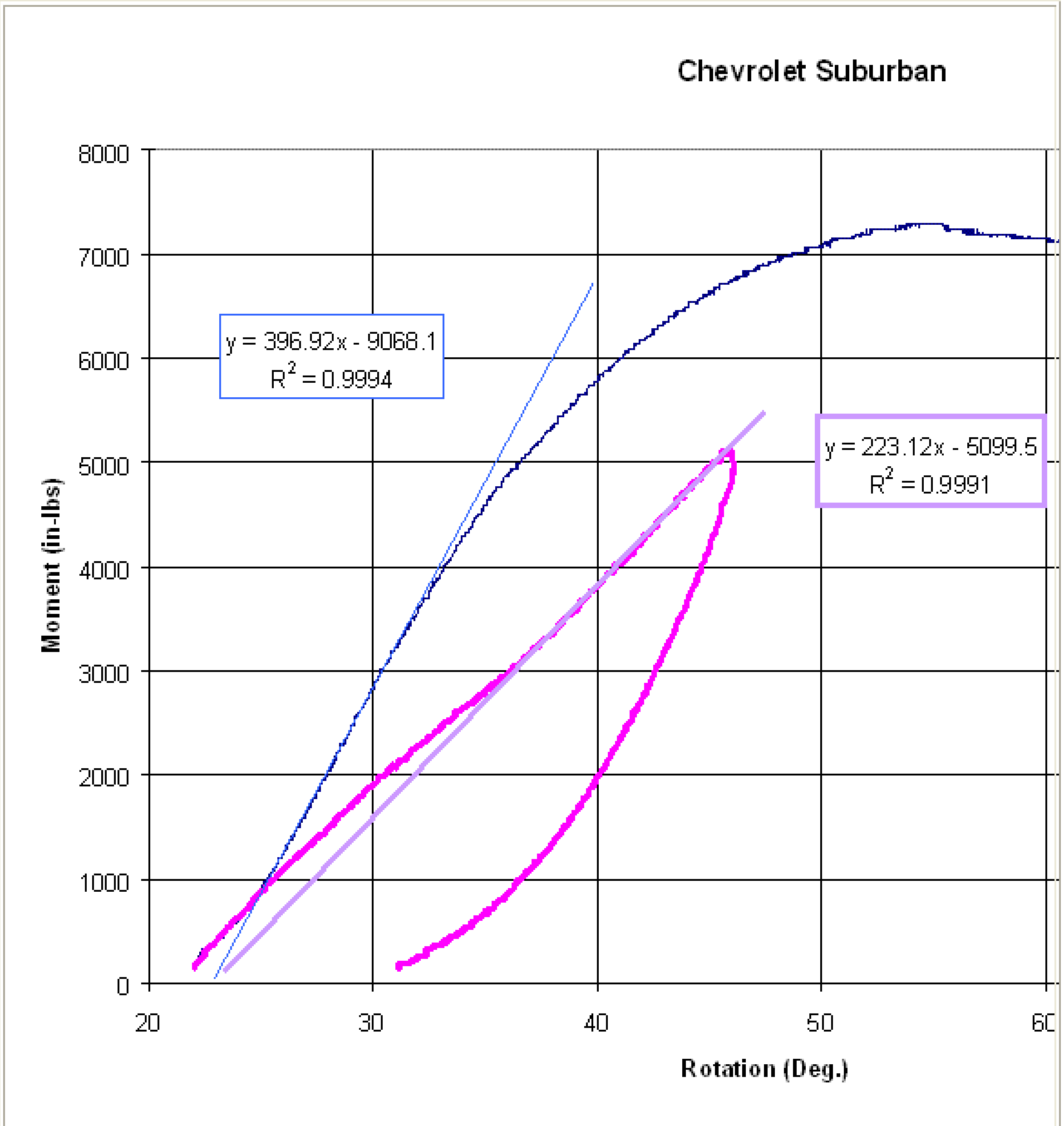
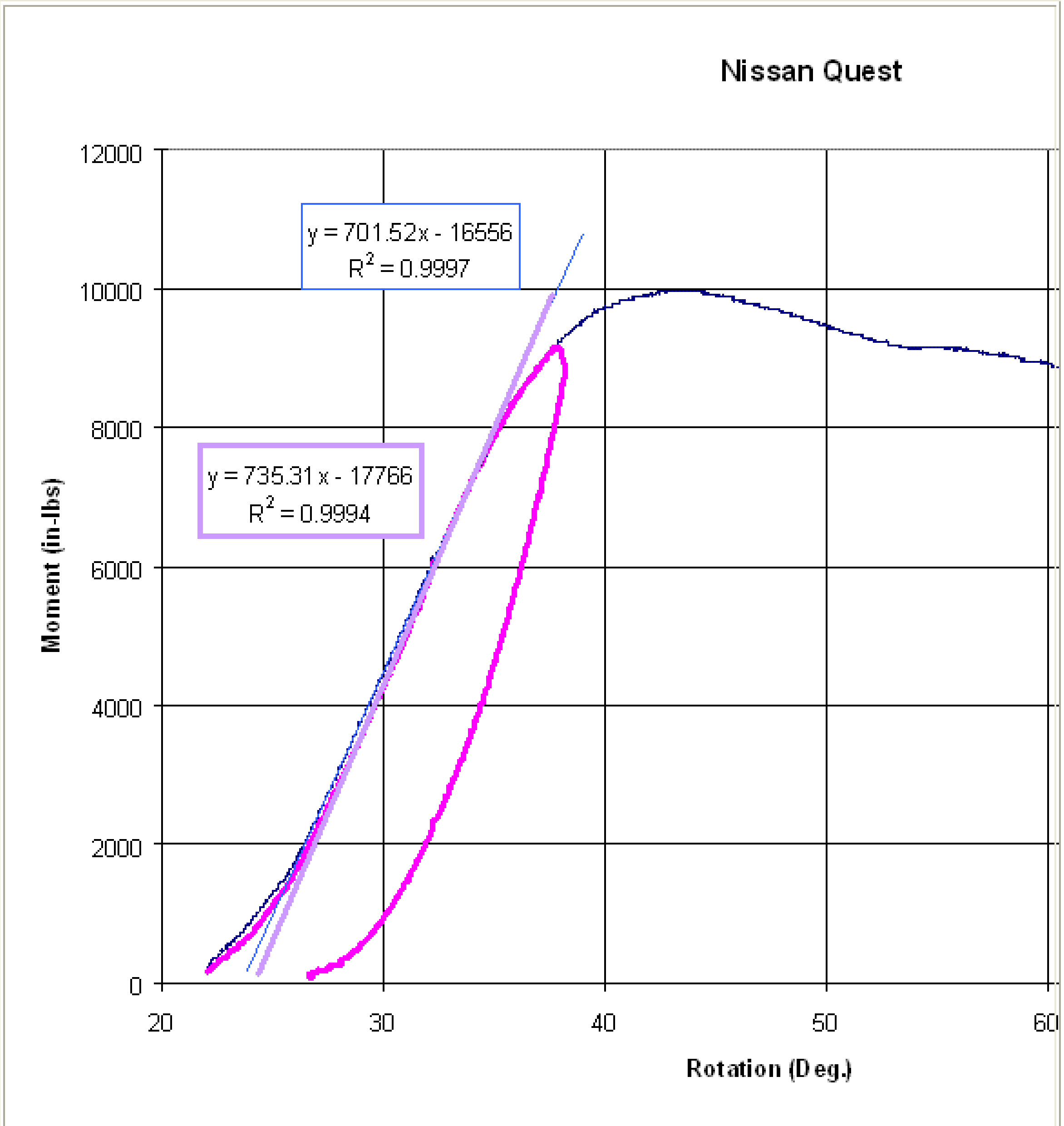
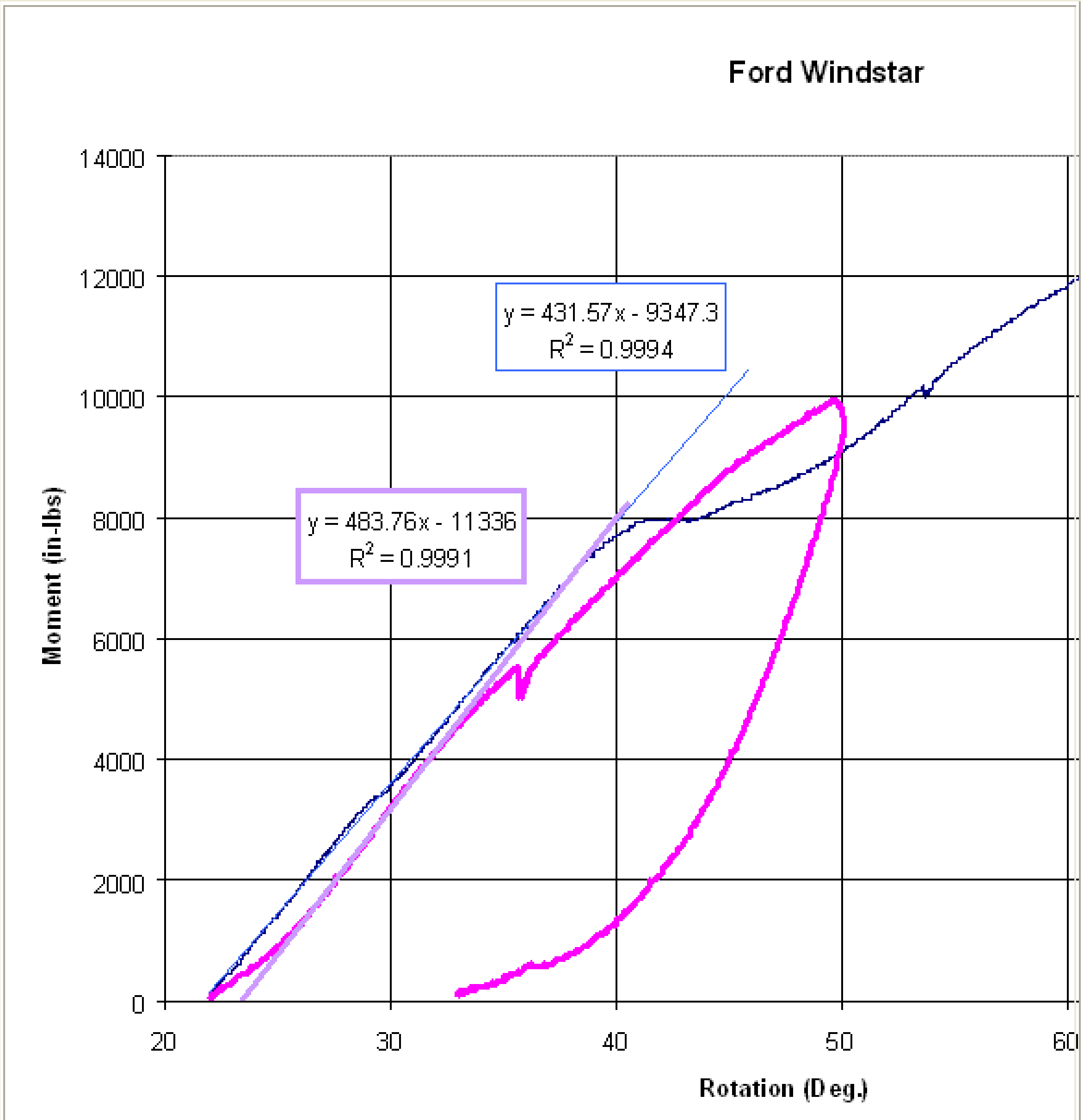

Chevrolet Suburban
y = 396.92x - 9068.1
R2 = 0.9994
y = 223.12x - 5099.5
R2 = 0.9991
Moment (in-lbs)
Rotation (Deg.)
8000
7000
6000
5000
4000
3000
2000
1000
0
20
30
40
50
60

Figure A2



Nissan Quest
y = 701.52x - 16556
R2 = 0.9997
y = 735.31x - 17766
R2 = 0.9994
Moment (in-lbs)
12000
10000
8000
6000
4000
2000
0
20
30
40
50
60
Rotation (Deg.)

Figure A3



Ford Windstar
y = 431.57x - 9347.3
R^2 = 0.9994
y = 483.76x - 11336
R^2 = 0.9991
Moment (in-lbs)
14000
12000
10000
8000
6000
4000
2000
0
20
30
40
50
60
Rotation (Deg.)

Figure A4

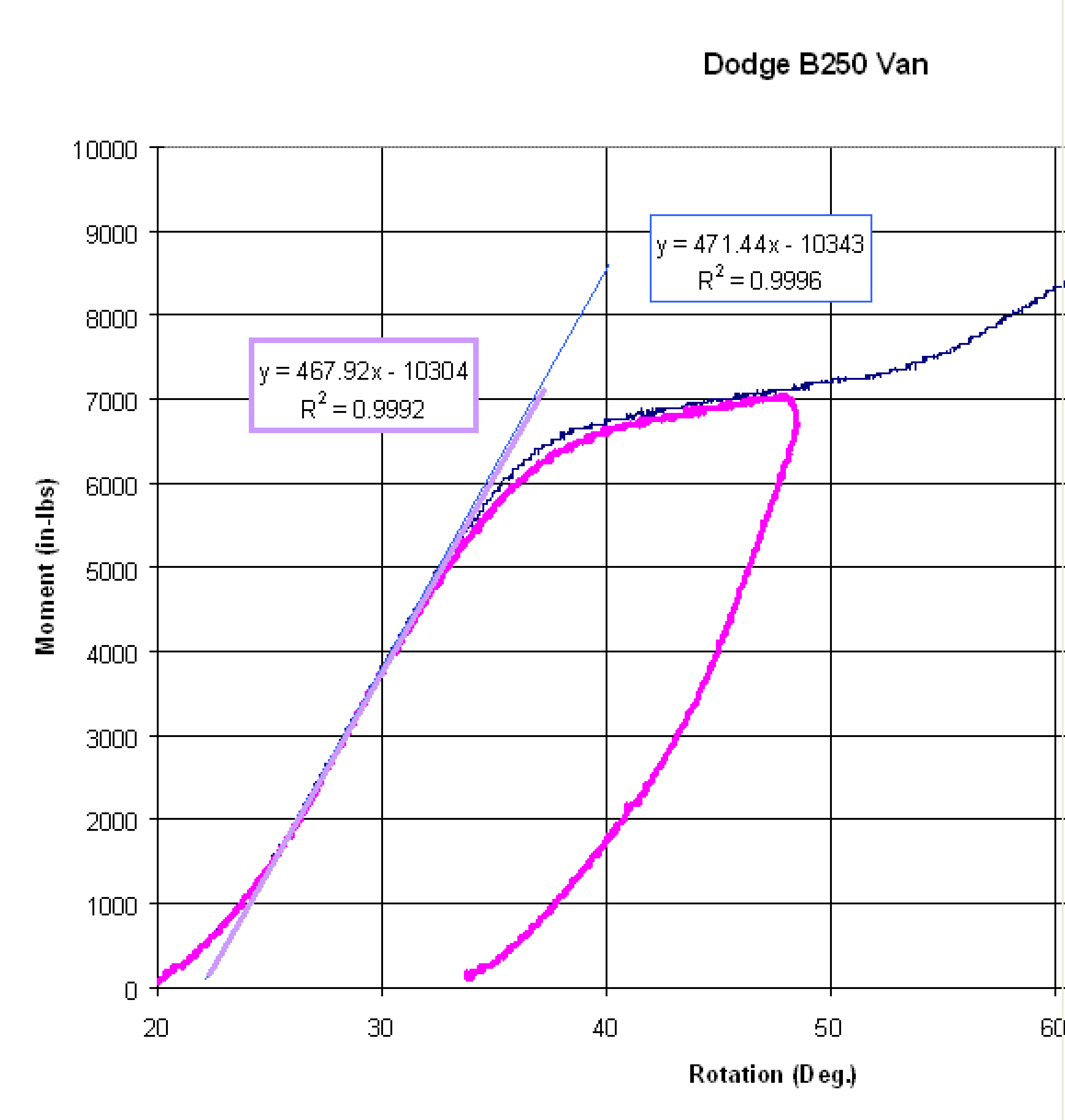

Dodge B250 Van
y = 471.44x - 10343
R2 = 0.9996
y = 467.92x - 10304
R2 = 0.9992
Moment (in-lbs)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
20
30
40
50
60
Rotation (Deg.)

Figure A5

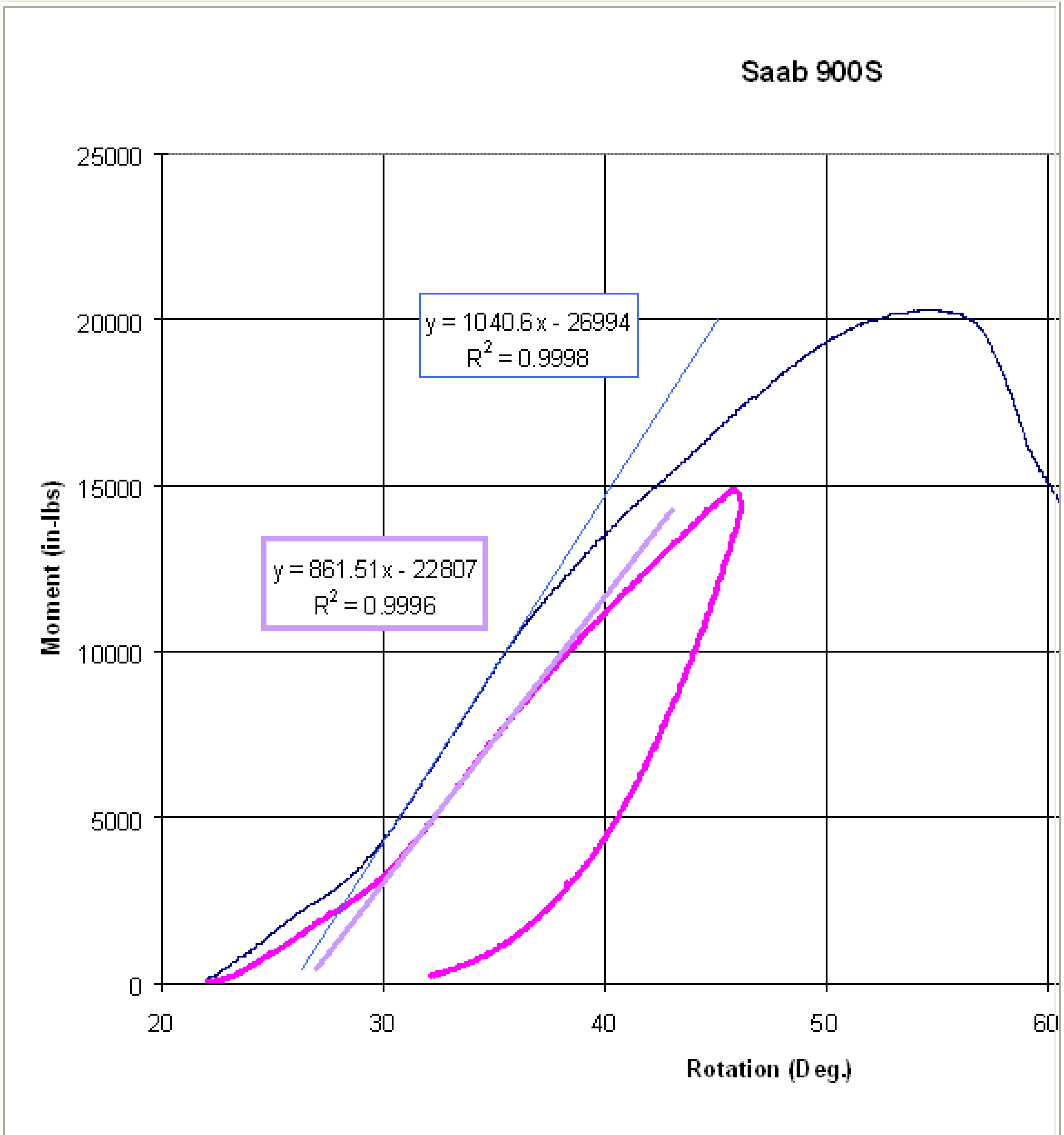

Saab 900S
y = 1040.6x - 26994
$R^2 = 0.9998$
y = 861.51x - 22807
$R^2 = 0.9996$
Moment (in-lbs)
25000
20000
15000
10000
5000
0
20
30
40
50
60
Rotation (Deg.)

Figure A6

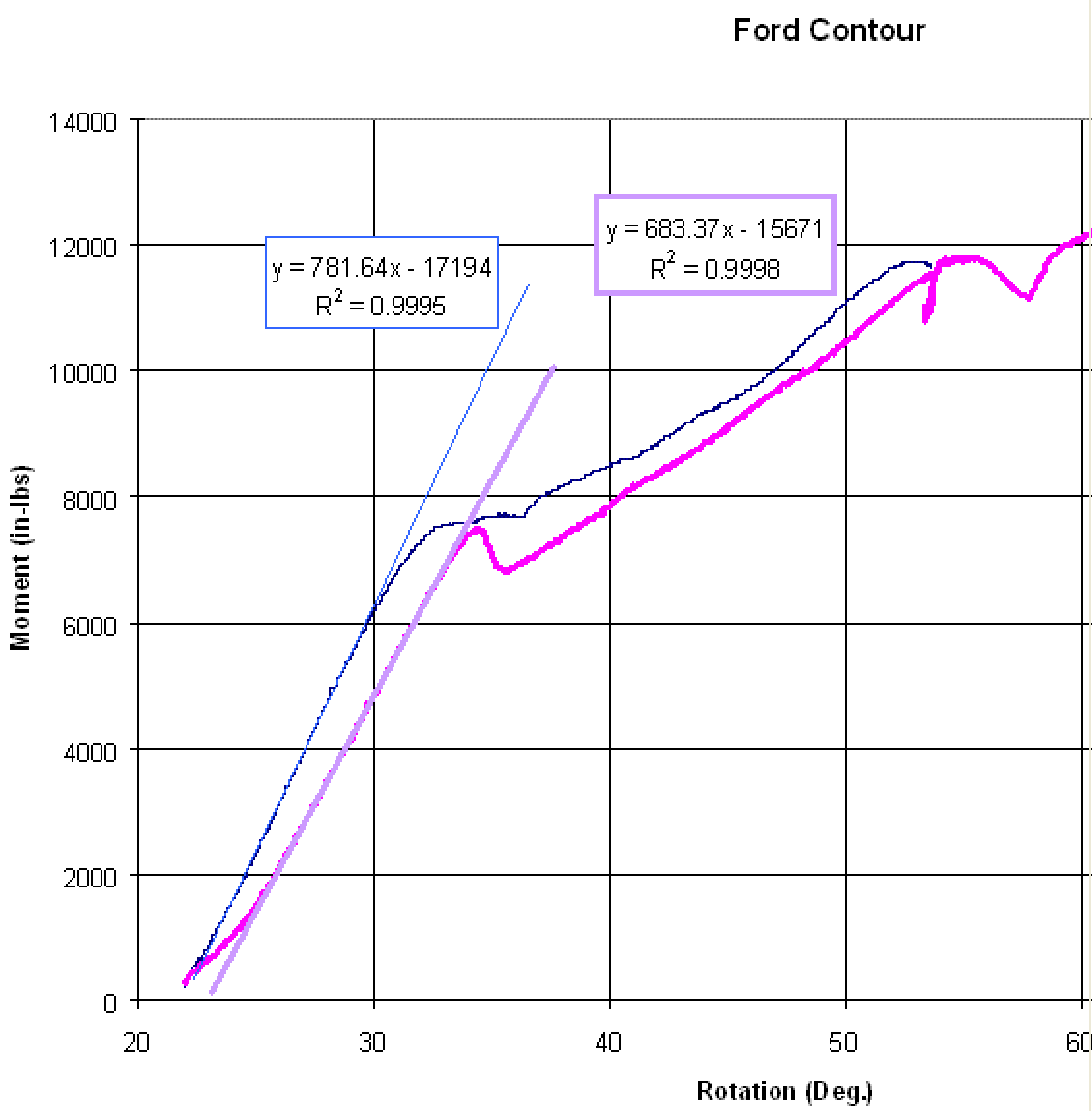
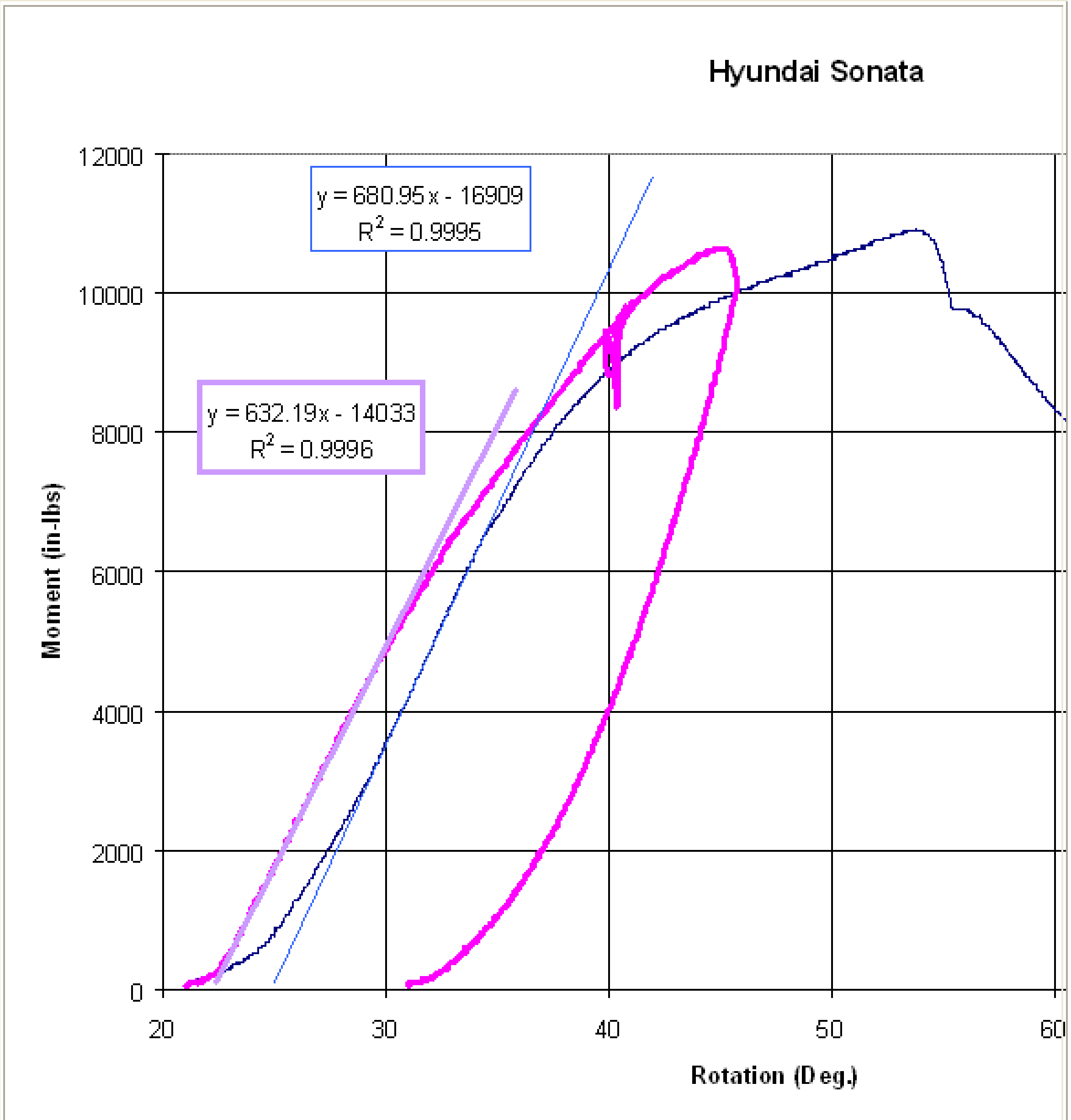
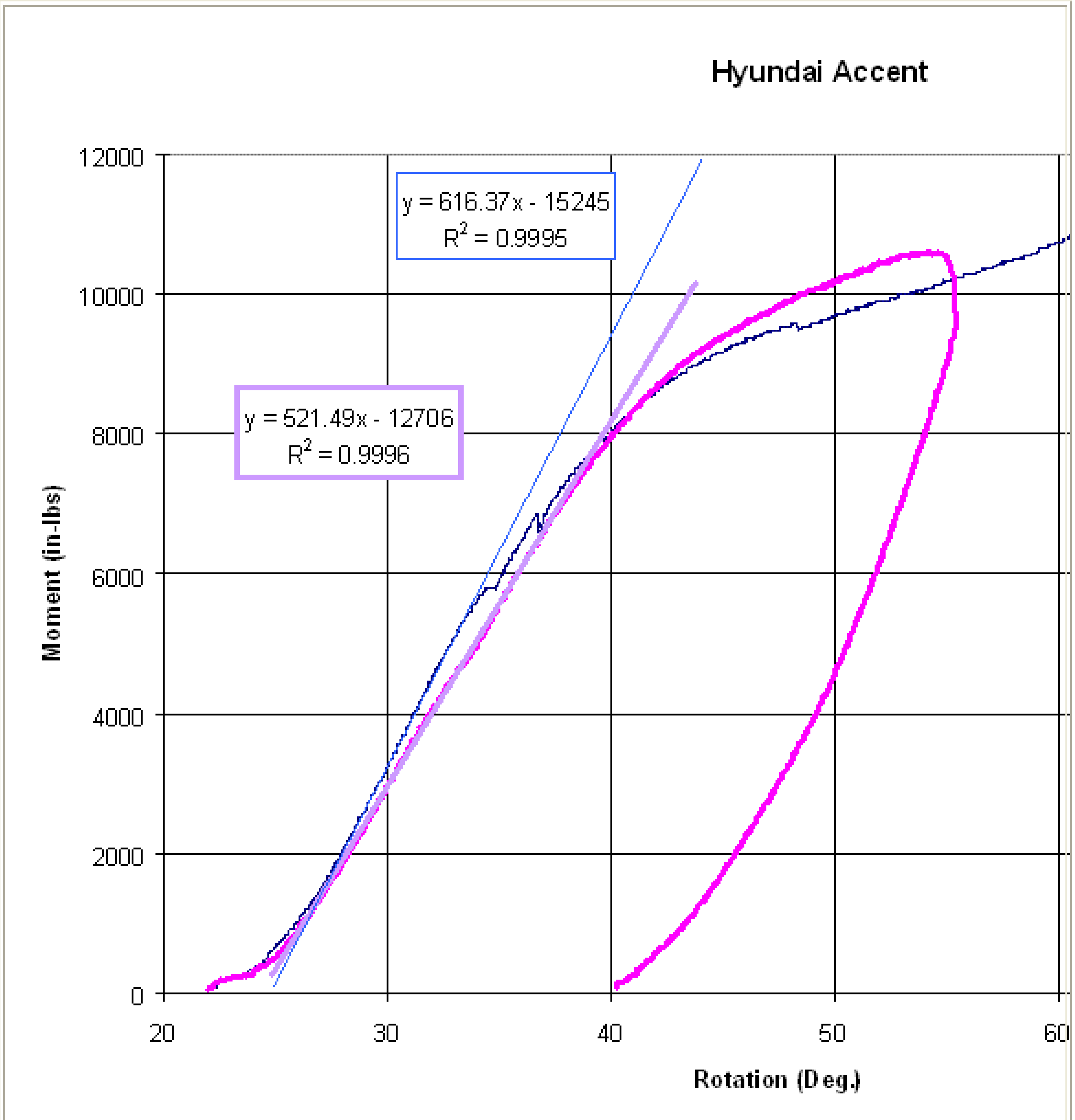

Ford Contour
y = 781.64x - 17194
R^2 = 0.9995
y = 683.37x - 15671
R^2 = 0.9998
14000
12000
10000
8000
6000
4000
2000
0
Moment (in-lbs)
20
30
40
50
60
Rotation (Deg.)

Figure A7



Hyundai Sonata
y = 680.95x - 16909
R2 = 0.9995
y = 632.19x - 14033
R2 = 0.9996
Moment (in-lbs)
12000
10000
8000
6000
4000
2000
0
20
30
40
50
60
Rotation (Deg.)

Figure A8



Hyundai Accent
y = 616.37x - 15245
R^2 = 0.9995
y = 521.49x - 12706
R^2 = 0.9996
Moment (in-lbs)
12000
10000
8000
6000
4000
2000
0
20
30
40
50
60
Rotation (Deg.)

Figure A9

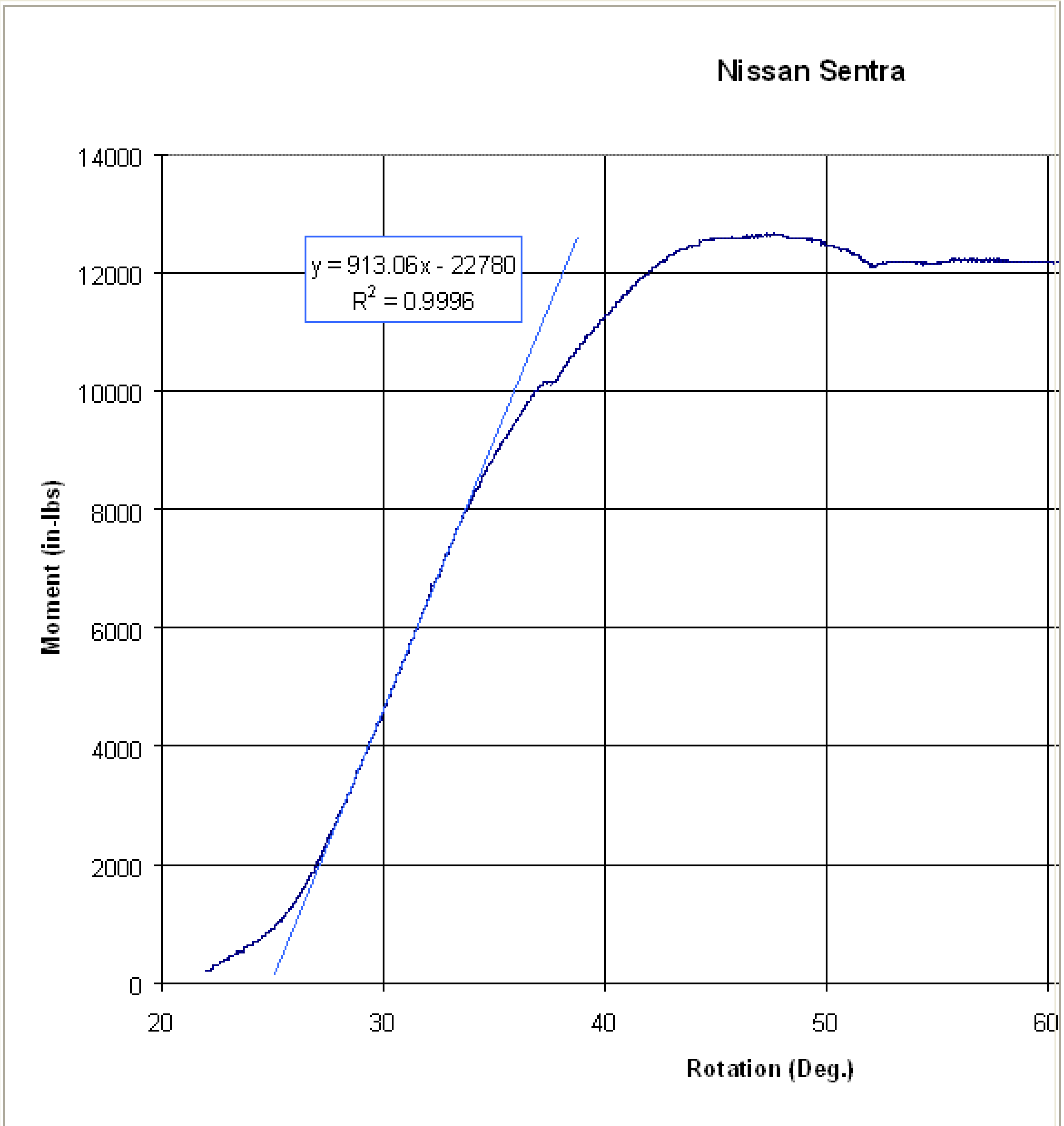
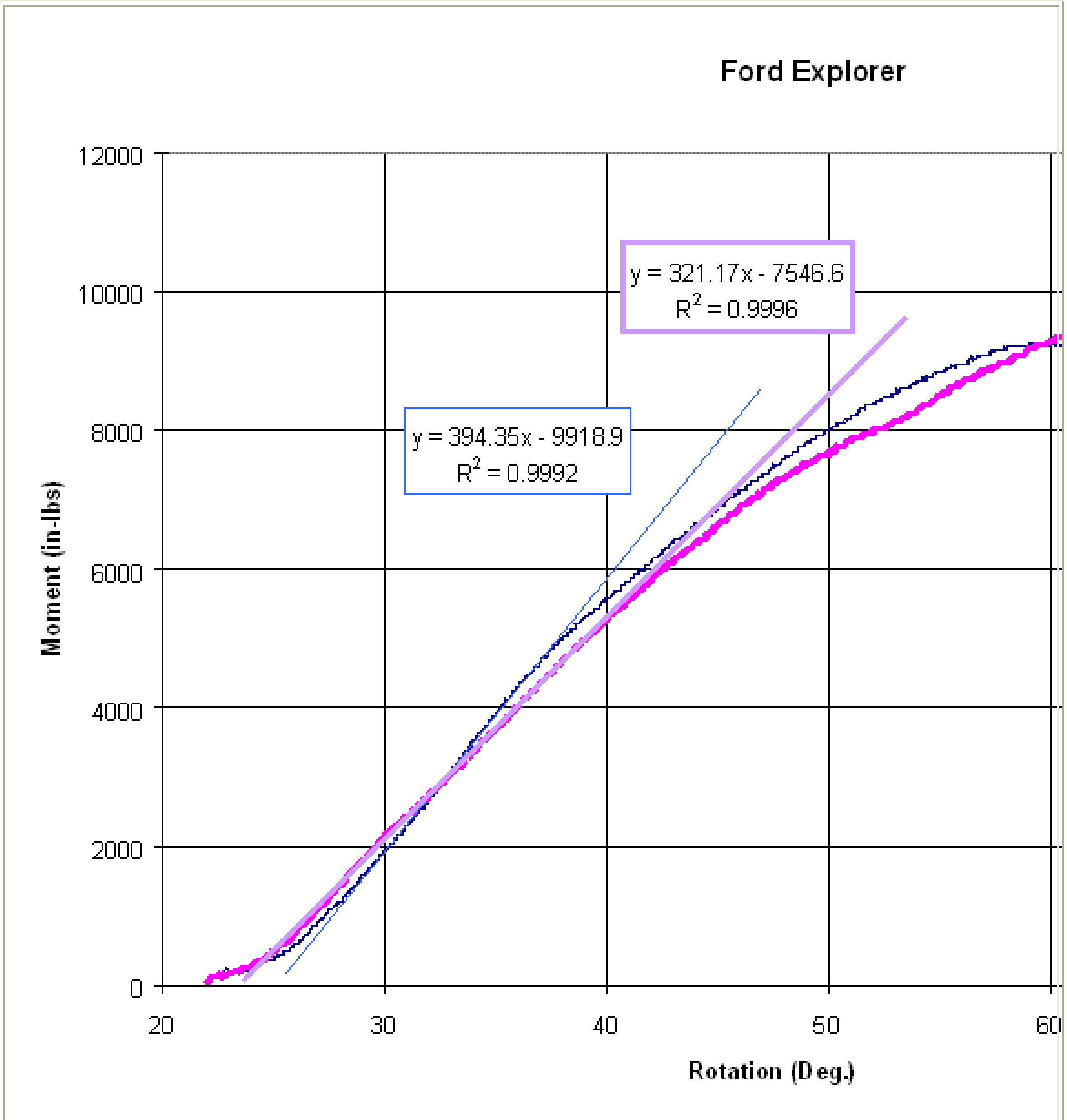

Nissan Sentra
y = 913.06x - 22780
R2 = 0.9996
14000
12000
10000
8000
6000
4000
2000
0
Moment (in-lbs)
20
30
40
50
60
Rotation (Deg.)

Figure A10



Ford Explorer
12000
10000
8000
6000
4000
2000
0
Moment (in-lbs)
20
30
40
50
60
Rotation (Deg.)
y = 321.17x - 7546.6
R2 = 0.9996
y = 394.35x - 9918.9
R2 = 0.9992

Figure A11

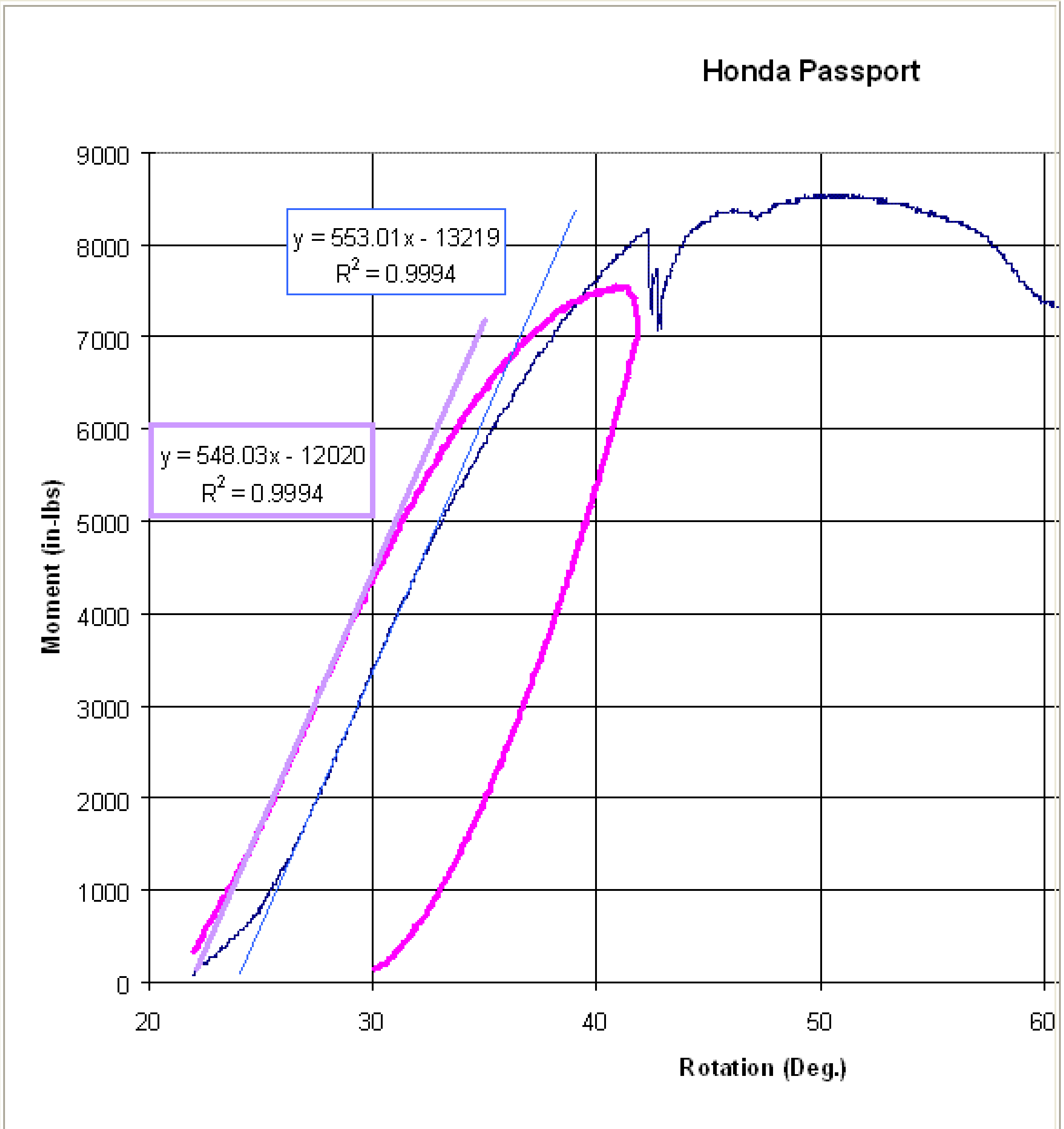

Honda Passport
y = 553.01x - 13219
R2 = 0.9994
y = 548.03x - 12020
R2 = 0.9994
Moment (in-lbs)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
20
30
40
50
60
Rotation (Deg.)

Figure A12

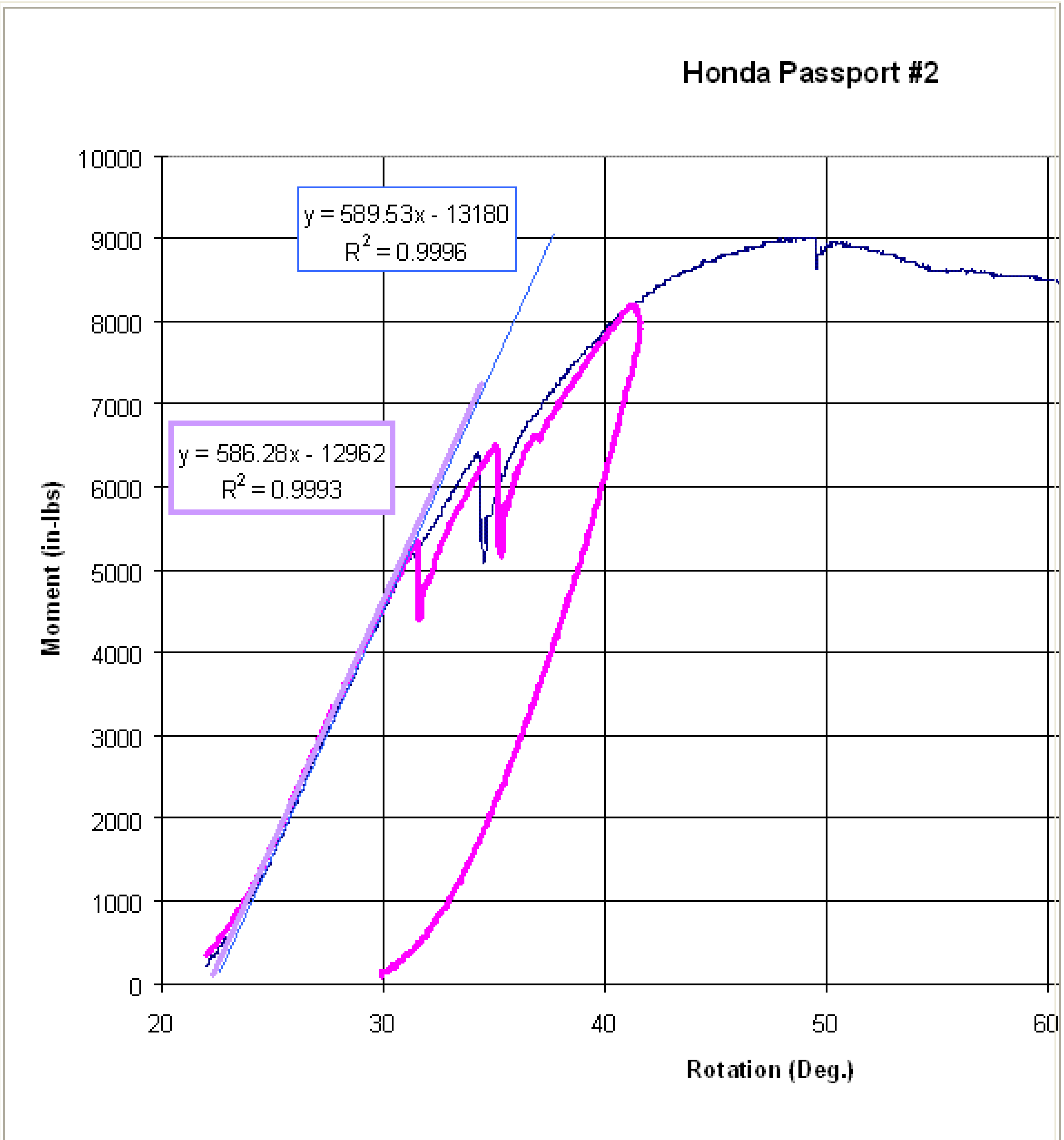


Figure A13

Appendix A Part 2

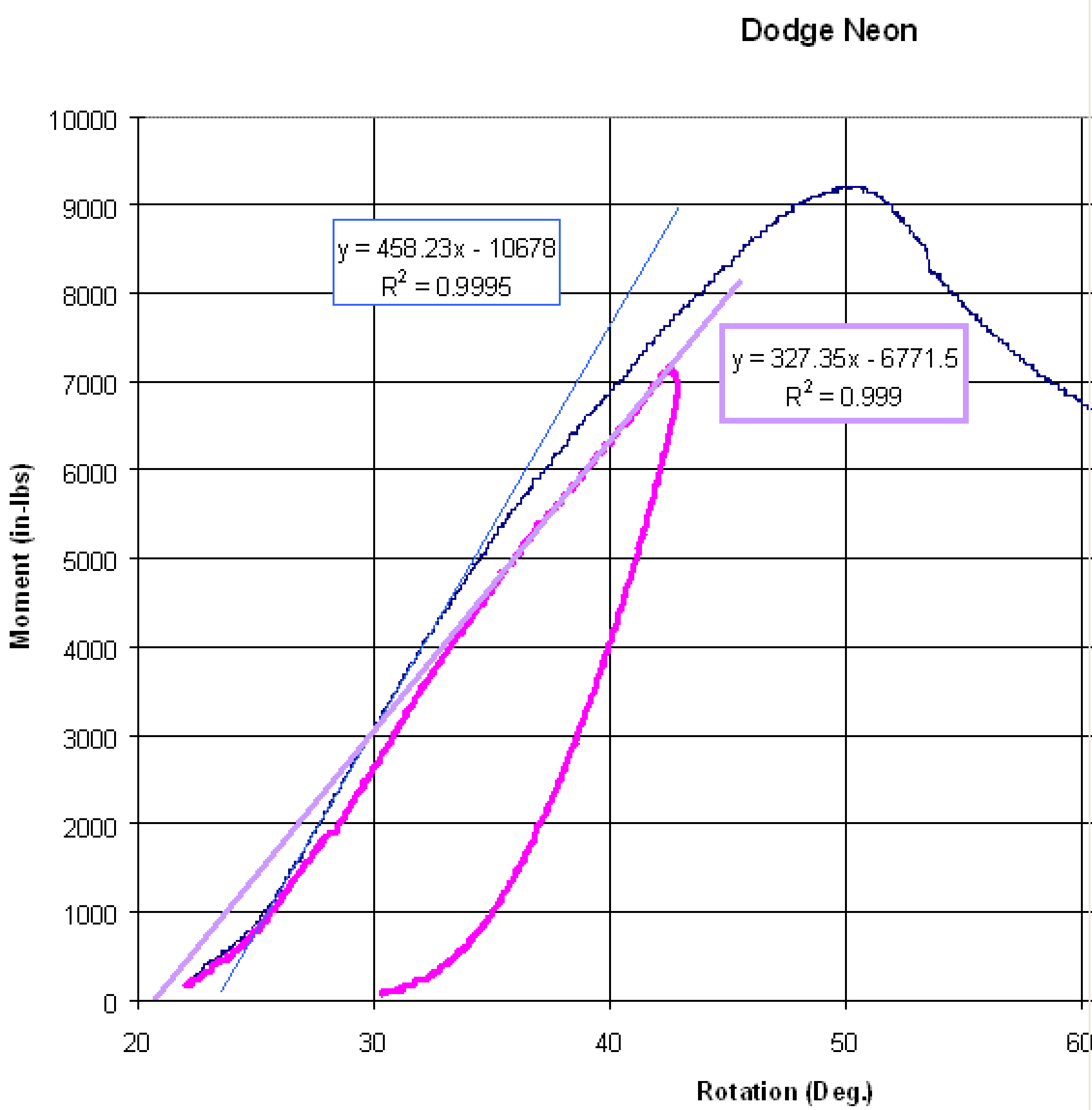

Dodge Neon
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Moment (in-lbs)
y = 458.23x - 10678
R^2 = 0.9995
y = 327.35x - 6771.5
R^2 = 0.999
20
30
40
50
60
Rotation (Deg.)

Figure A14

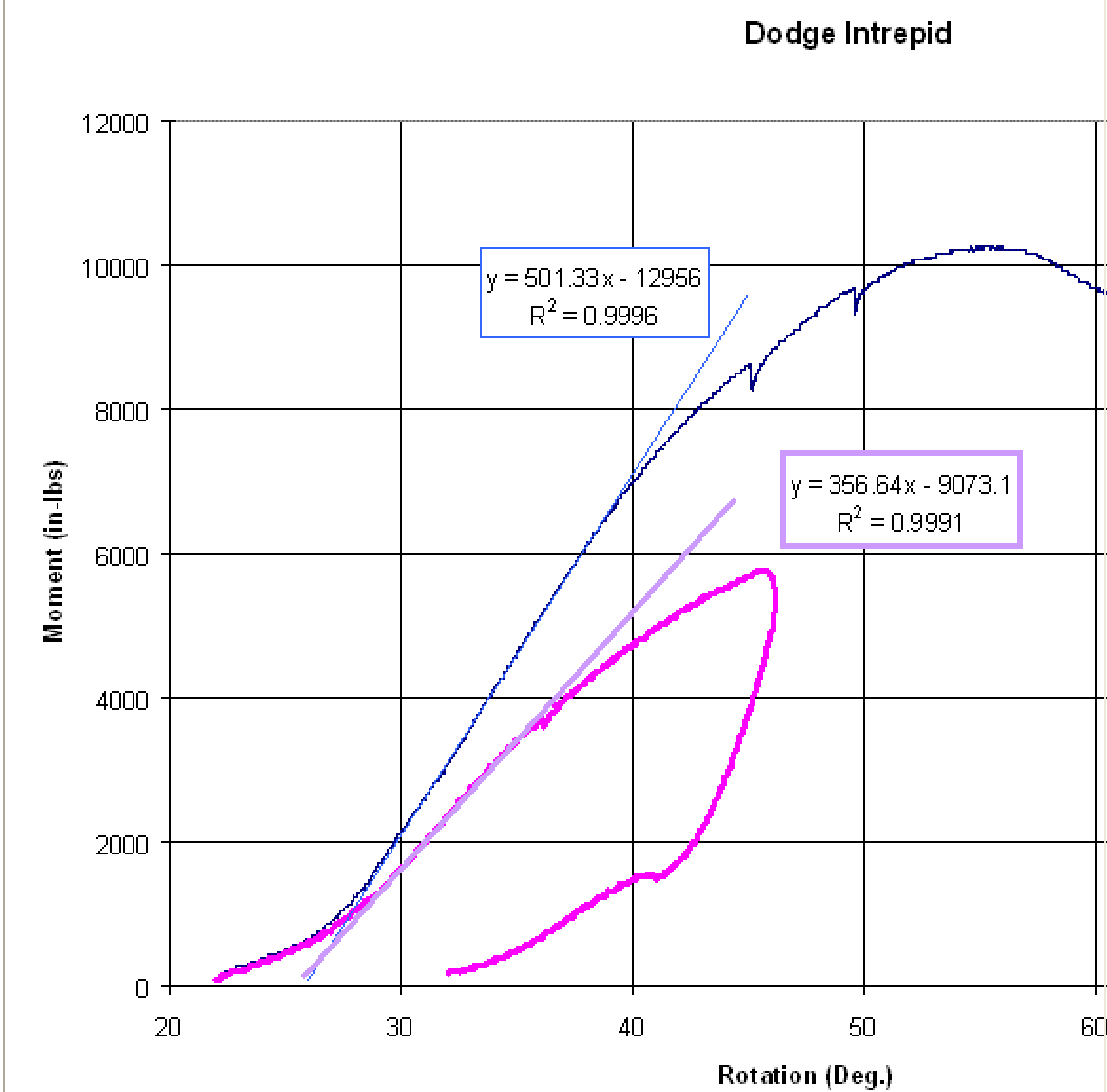
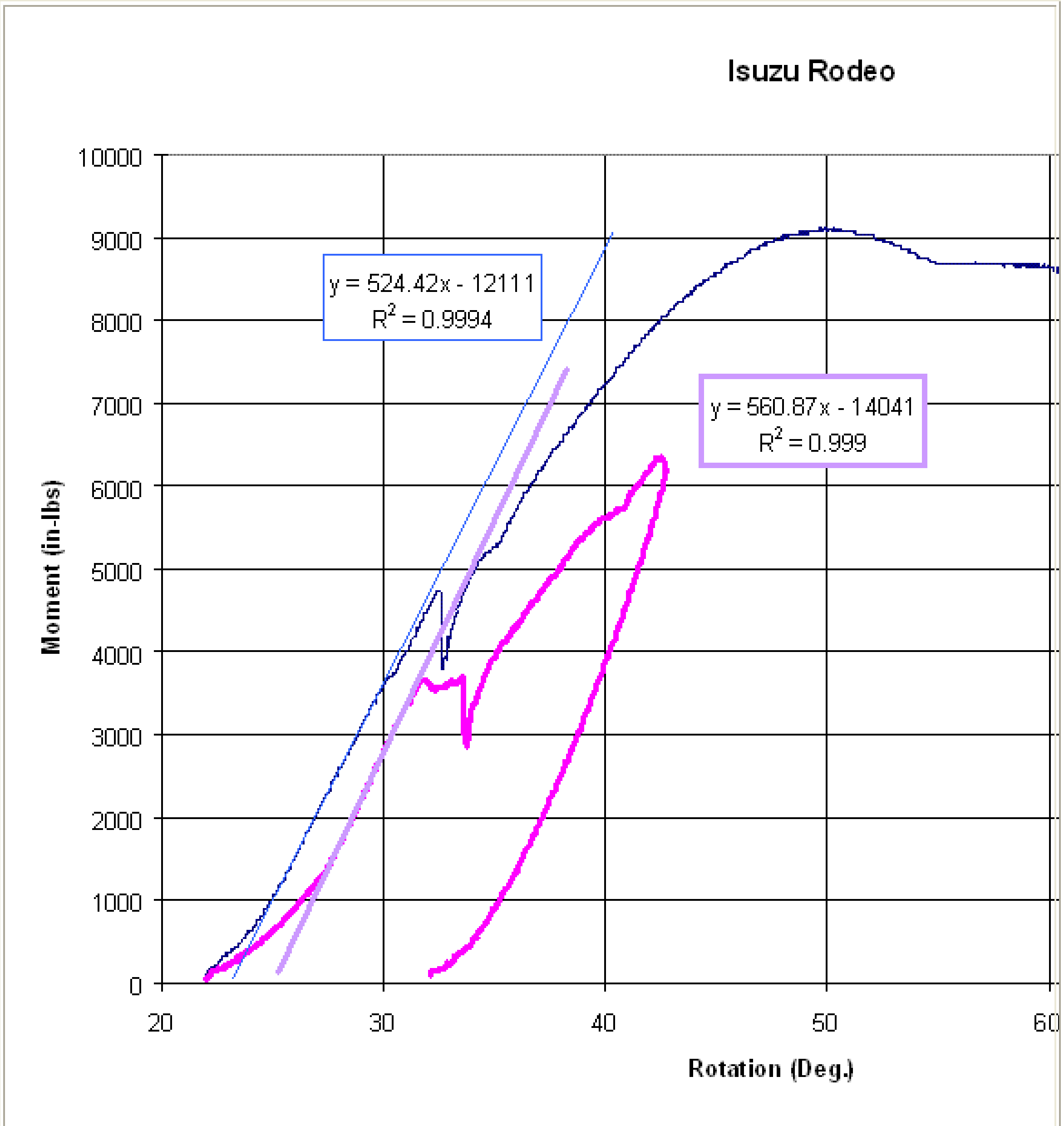

Dodge Intrepid
y = 501.33x - 12956
R² = 0.9996
y = 356.64x - 9073.1
R² = 0.9991
Moment (in-lbs)
12000
10000
8000
6000
4000
2000
0
20
30
40
50
60
Rotation (Deg.)

Figure A15



Isuzu Rodeo
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Moment (in-lbs)
y = 524.42x - 12111
R^2 = 0.9994
y = 560.87x - 14041
R^2 = 0.999
20
30
40
50
60
Rotation (Deg.)

Figure A16

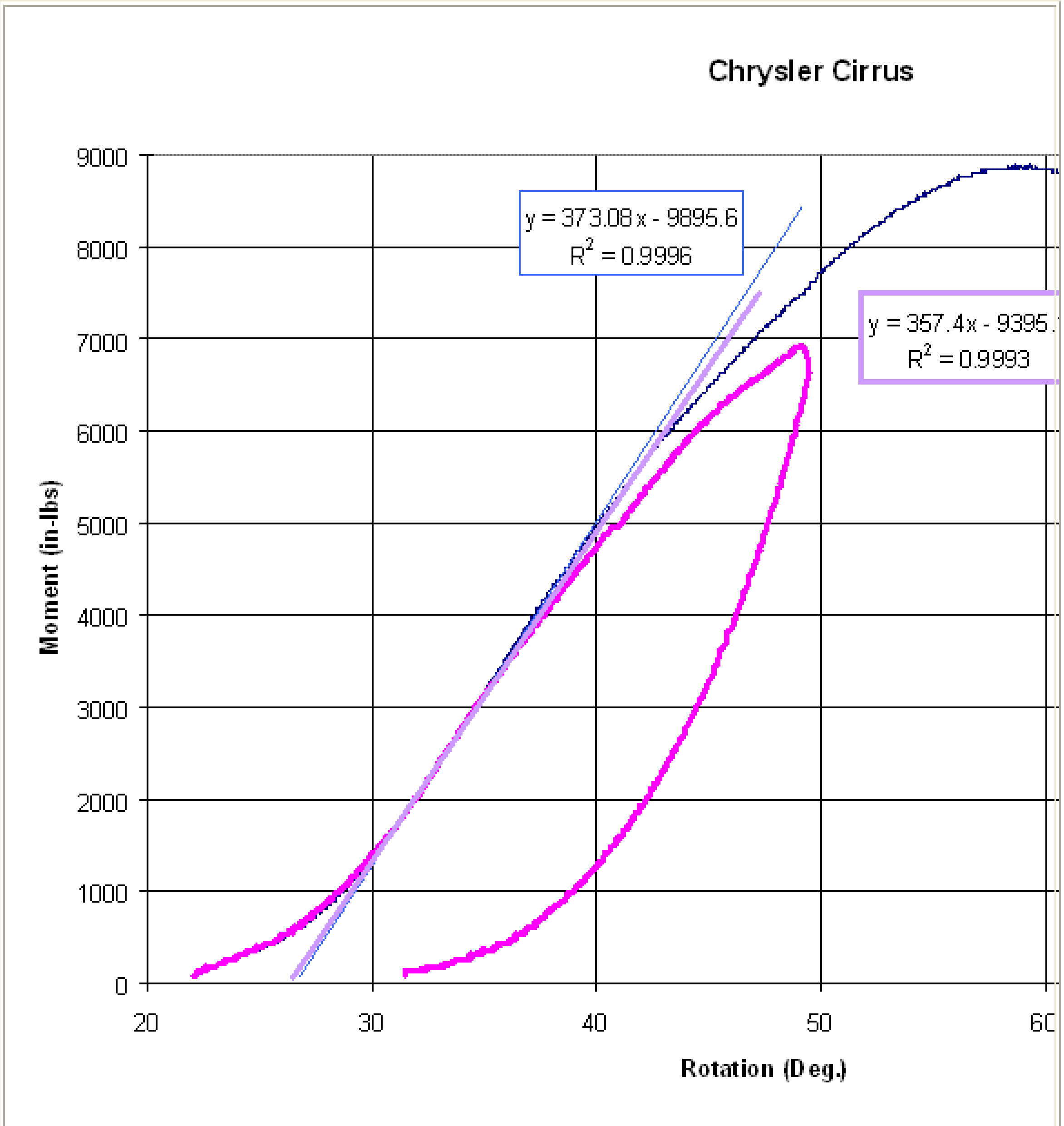
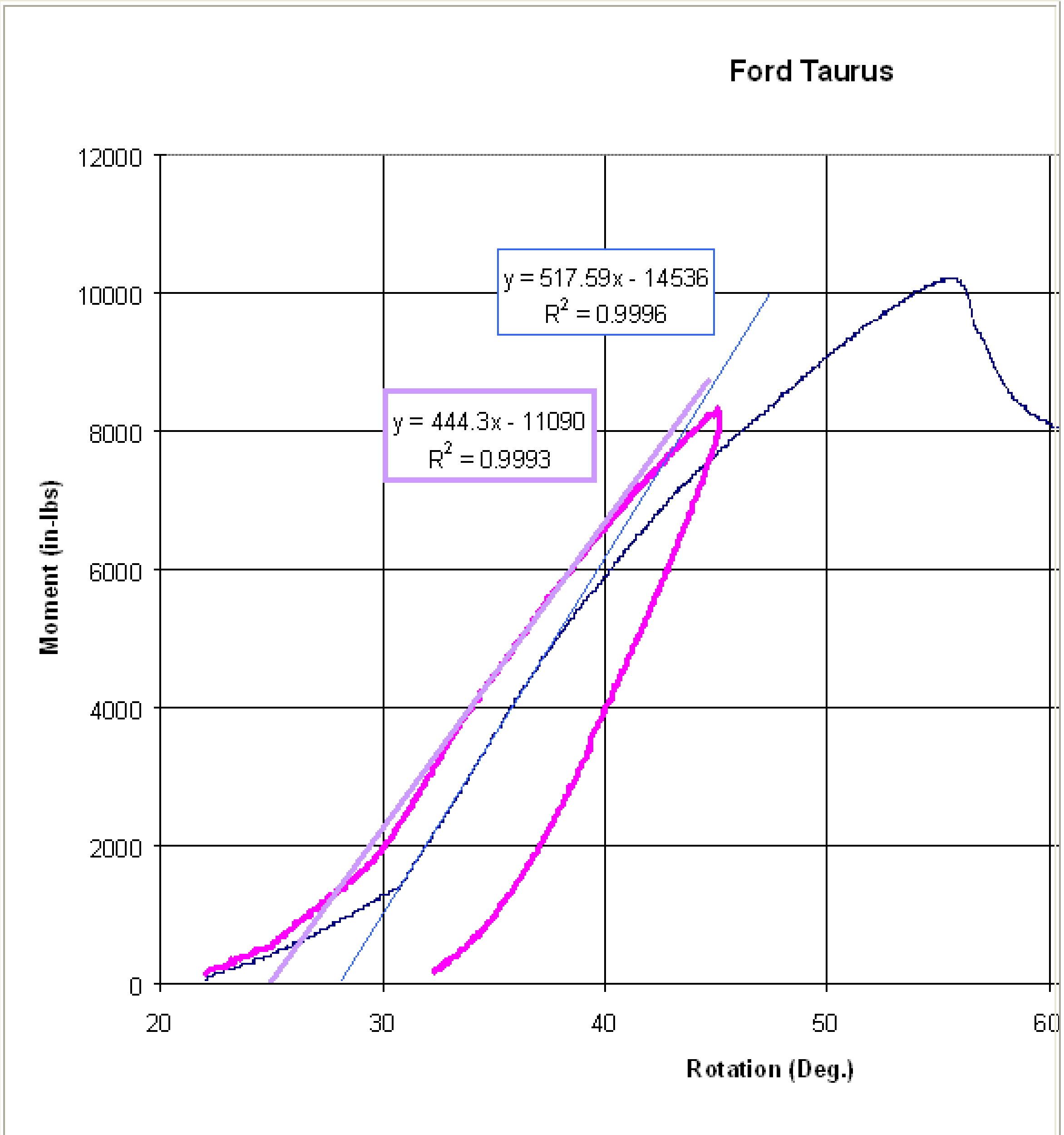
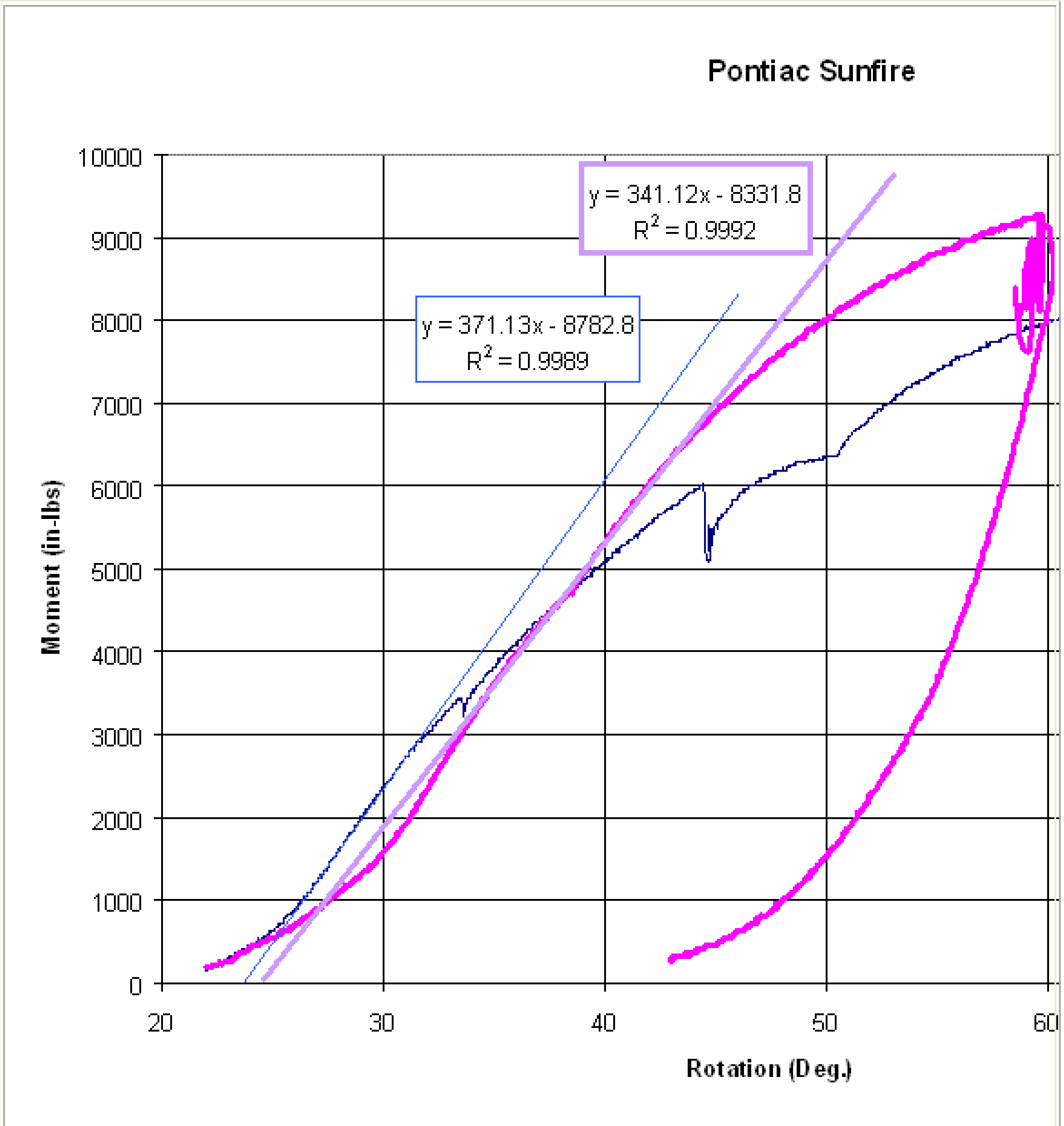

Chrysler Cirrus
y = 373.08x - 9895.6
R2 = 0.9996
y = 357.4x - 9395.
R2 = 0.9993
Moment (in-lbs)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
20
30
40
50
60
Rotation (Deg.)

Figure A17


Ford Taurus
y = 517.59x - 14536
R2 = 0.9996
y = 444.3x - 11090
R2 = 0.9993
Moment (in-lbs)
Rotation (Deg.)
12000
10000
8000
6000
4000
2000
0
20
30
40
50
60
Figure A18



Pontiac Sunfire
y = 341.12x - 8331.8
R2 = 0.9992
y = 371.13x - 8782.8
R2 = 0.9989
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Moment (in-lbs)
20
30
40
50
60
Rotation (Deg.)

Figure A19

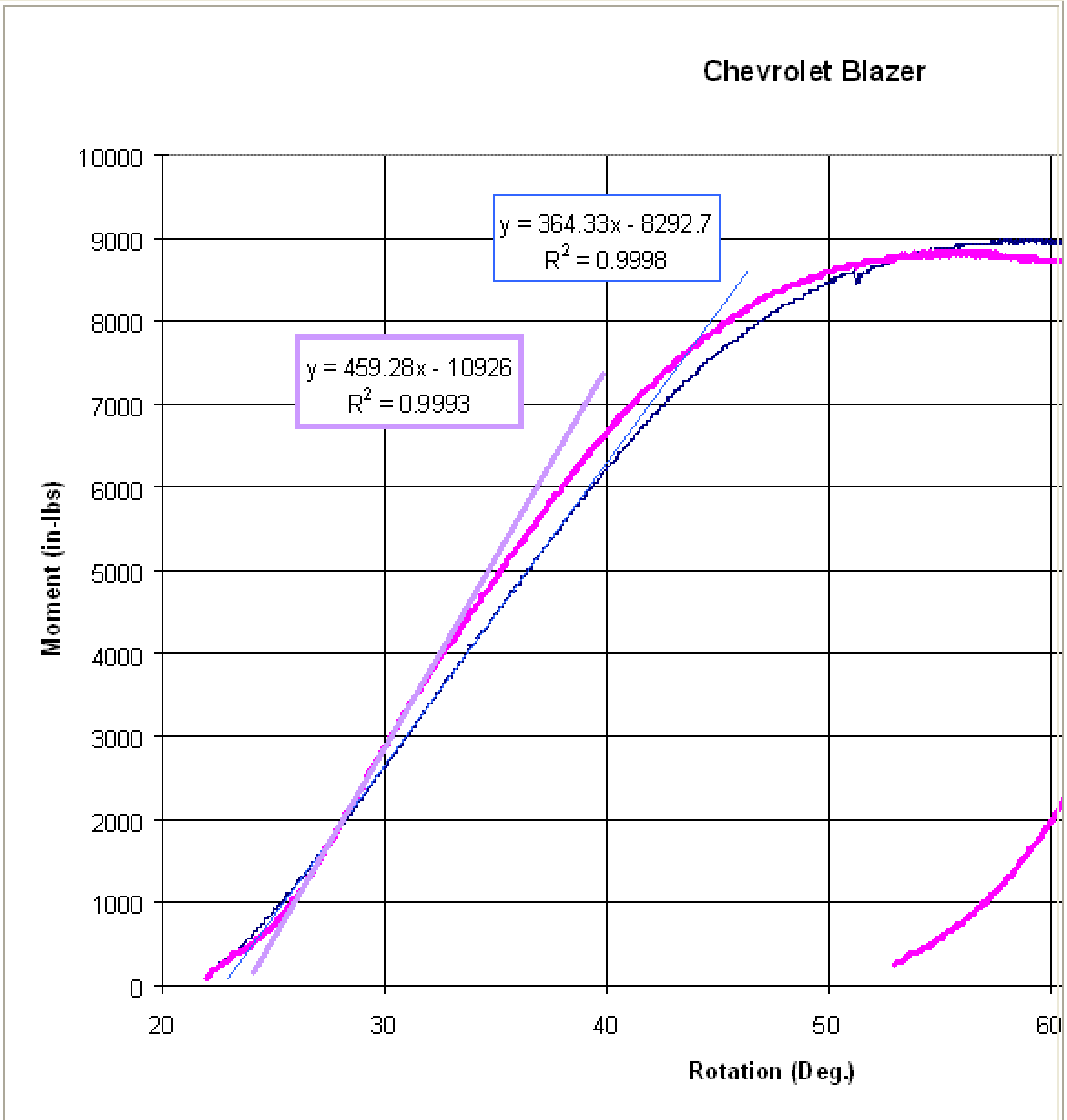
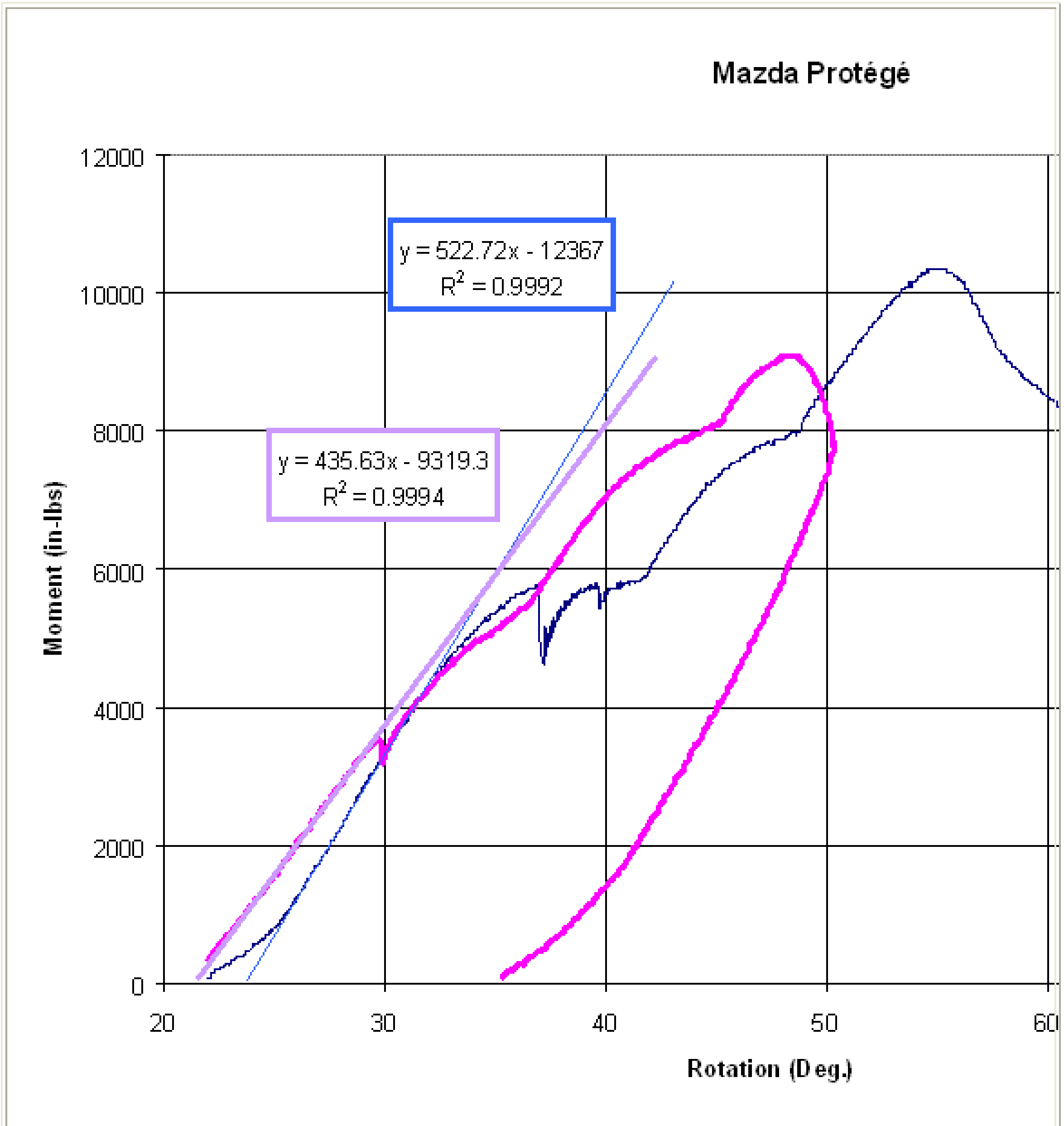

Chevrolet Blazer
y = 364.33x - 8292.7
R² = 0.9998
y = 459.28x - 10926
R² = 0.9993
Moment (in-lbs)
Rotation (Deg.)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
20
30
40
50
60

Figure A20



Mazda Protégé
y = 522.72x - 12367
R2 = 0.9992
y = 435.63x - 9319.3
R2 = 0.9994
Moment (in-lbs)
12000
10000
8000
6000
4000
2000
0
20
30
40
50
60
Rotation (Deg.)

Figure A21

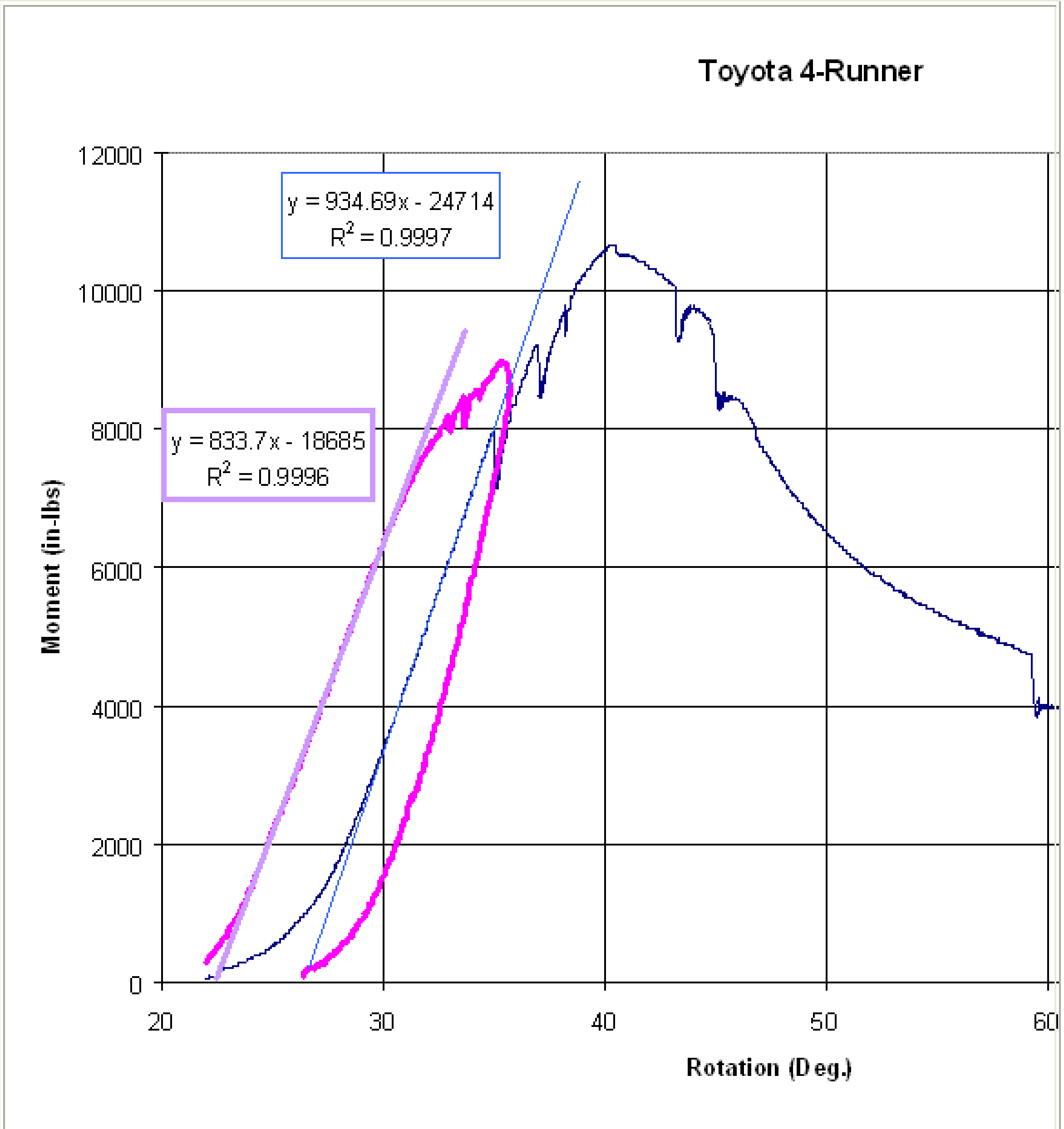
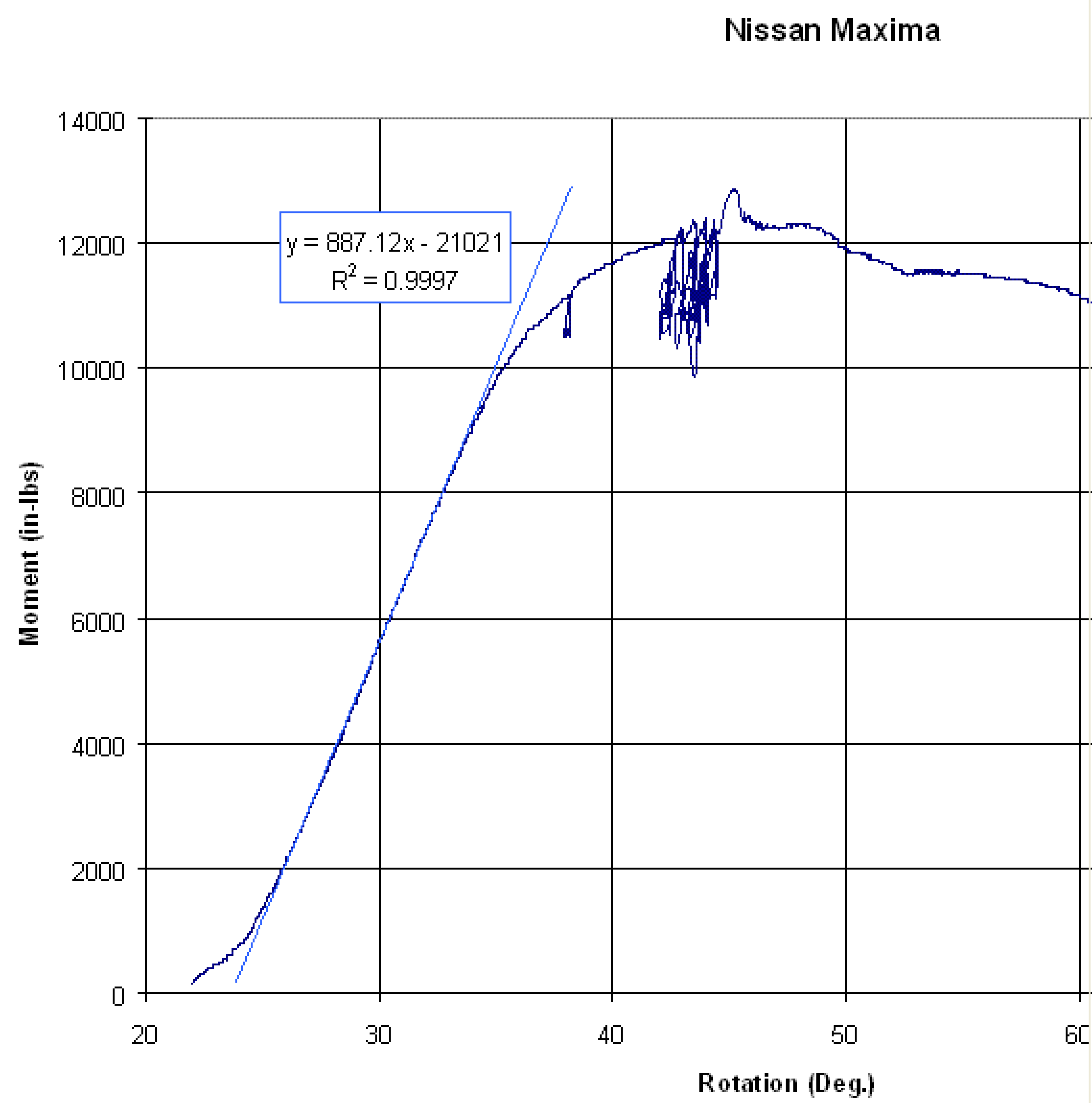
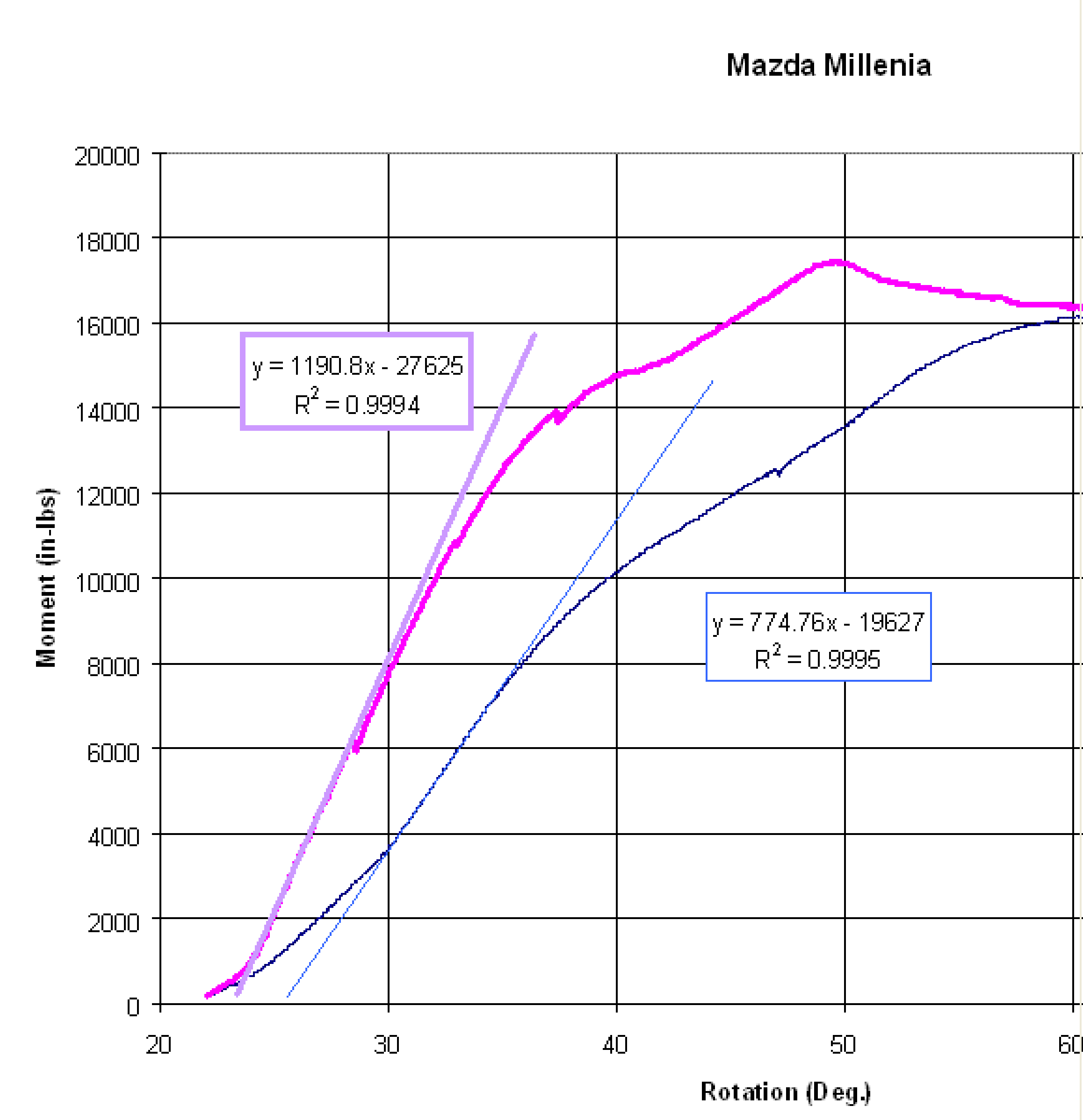

Toyota 4-Runner
y = 934.69x - 24714
R^2 = 0.9997
y = 833.7x - 18685
R^2 = 0.9996
Moment (in-lbs)
12000
10000
8000
6000
4000
2000
0
20
30
40
50
60
Rotation (Deg.)

Figure A22



Nissan Maxima
y = 887.12x - 21021
R2 = 0.9997
Moment (in-lbs)
14000
12000
10000
8000
6000
4000
2000
0
20
30
40
50
60
Rotation (Deg.)

Figure A23



Mazda Millenia
y = 1190.8x - 27625
$R^2 = 0.9994$
y = 774.76x - 19627
$R^2 = 0.9995$
Moment (in-lbs)
Rotation (Deg.)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
20
30
40
50
60

Figure A24

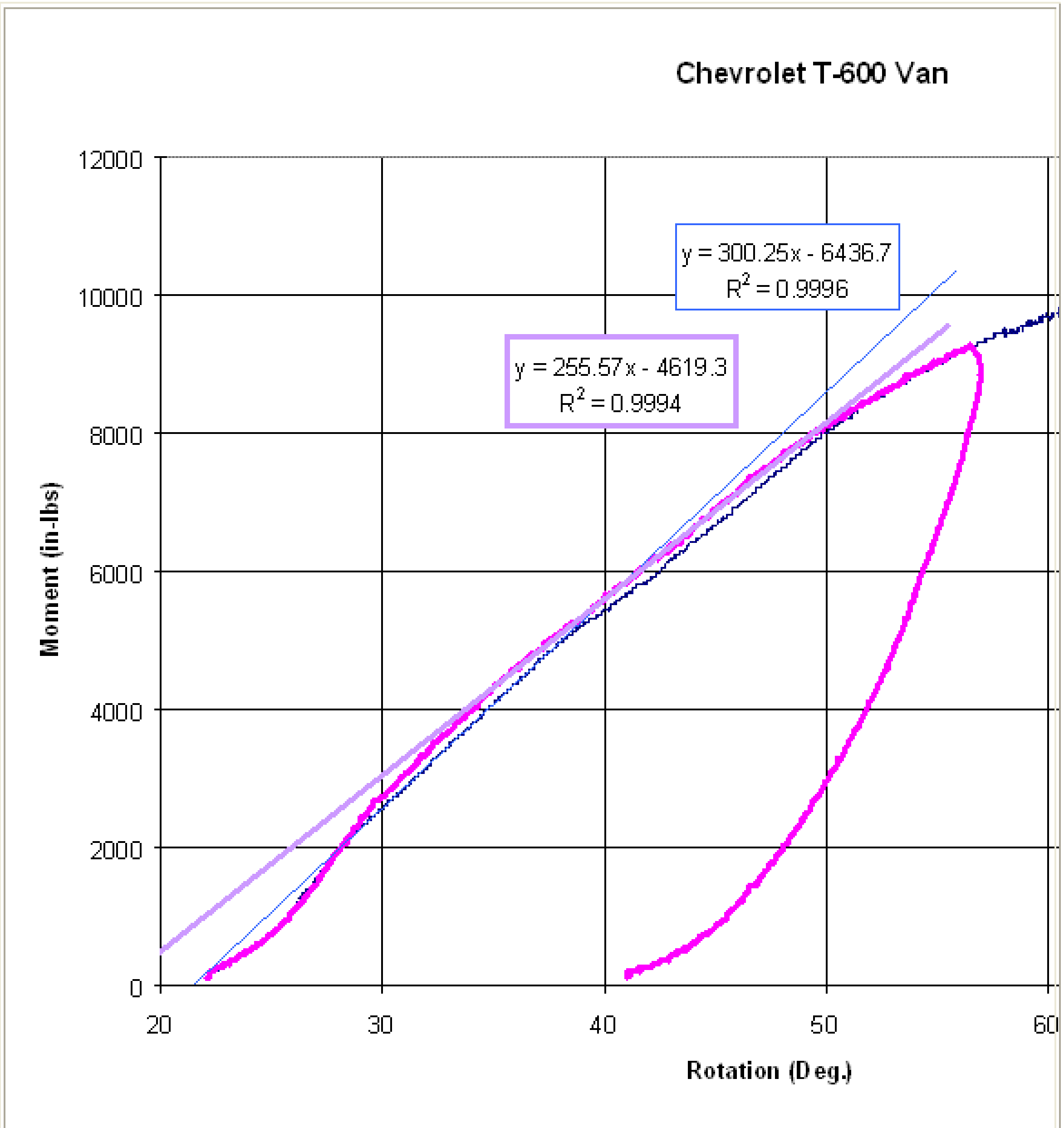
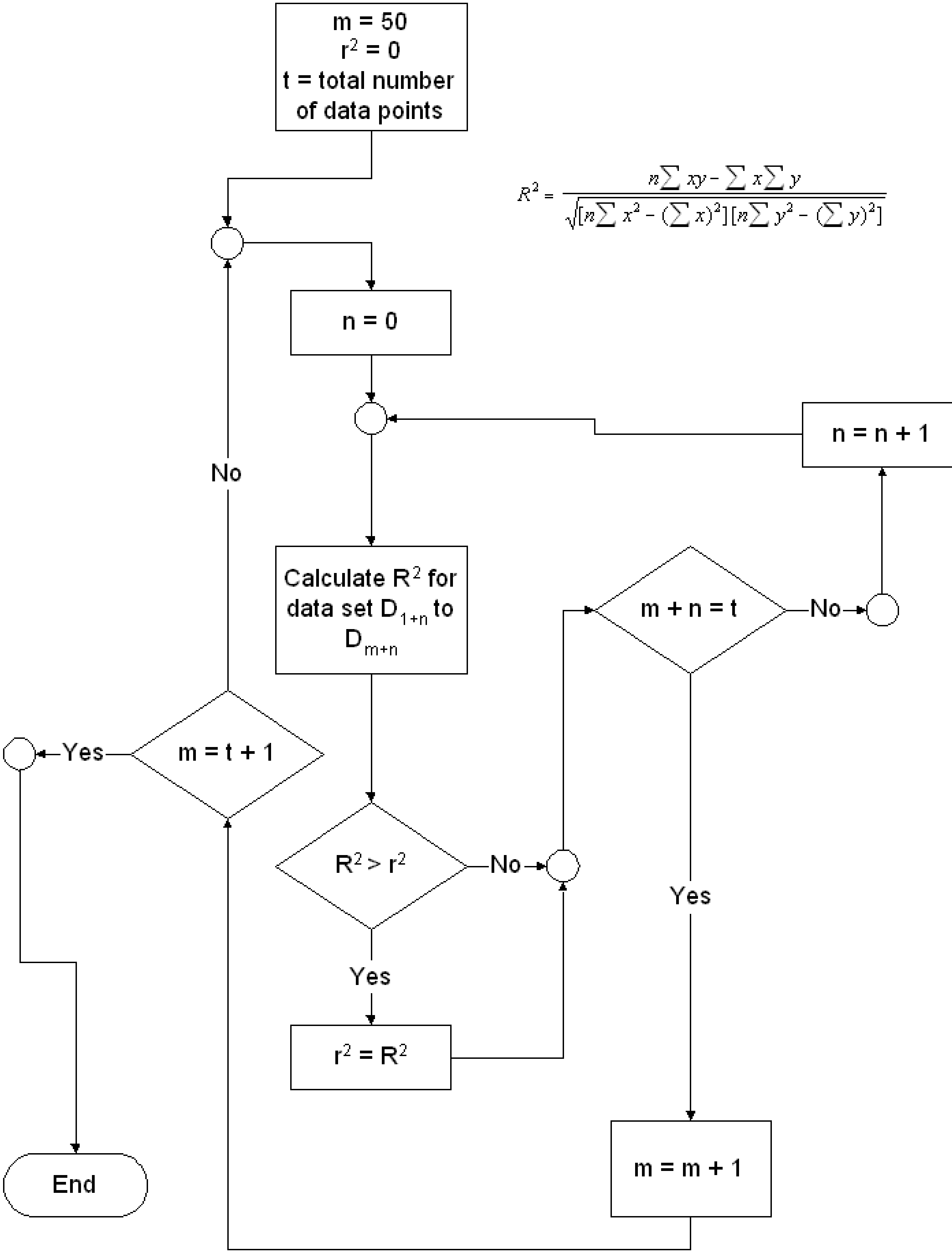


Figure A25

Appendix B


m = 50
r2 = 0
t = total number of data points
R2 = n∑xy − ∑x∑y / √[n∑x2 − (∑x)2][n∑y2 − (∑y)2]
n = 0
n = n + 1
No
Calculate R2 for data set D1+n to Dm+n
m + n = t
No
Yes
m = t + 1
Yes
R2 > r2
No
Yes
r2 = R2
m = m + 1
End

Appendix C

The following appendix contains the tabulated data for each of the seats tested. For most vehicles the front driver and passenger seat data are contained in a single table. In general, the data from the seat tested to failure are contained on the left side of the table and the data from the seat deflected to 75% of the ultimate load deflections are on the right side. This format was followed regardless of whether a driver or passenger seat was tested to failure.

	GM Astro Driver						
Stiffness = 216 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 216 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	31.98	2315	192	Delta 10 Deg			
Delta 20 Deg	42.01	4480	782	Delta 20 Deg			
Delta 30 Deg	51.99	6297	1739	Delta 30 Deg			
Delta 40 Deg	61.99	7566	2957	Delta 40 Deg			
Delta 50 Deg	72.01	8611	4368				
FMVSS 207 Limit	36.52	3310	388	FMVSS 207 Limit			
5% Yield Strength	51.32	6172	1669	5% Yield Strength			
Ultimate Strength	72.01	8611	4368	Work Input			
				Energy Return			

	Chevy Suburban Driver			Chevy Suburban Passenger			
Stiffness = 397 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 223 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.00	3585	303	Delta 10 Deg	32.00	2284	223
Delta 20 Deg	42.02	6175	1184	Delta 20 Deg	42.02	4264	785
Delta 30 Deg	52.00	7230	2368	Delta 30 Deg			
Delta 40 Deg	62.02	6972	3625	Delta 40 Deg			
Delta 50 Deg	71.98	6354	4773				
FMVSS 207 Limit	31.19	3306	253	FMVSS 207 Limit	37.59	3314	493
5% Yield Strength	34.78	4502	499	5% Yield Strength			
Ultimate Strength	54.87	7290	2731	Work Input	46.08	4891	1121
				Energy Return			-316

	Nissan Quest Passenger			Nissan Quest Driver			

Stiffness = 702 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 735 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.02	5946	464	Delta 10 Deg	32.02	5753	432
Delta 20 Deg	42.02	9930	1953	Delta 20 Deg			
Delta 30 Deg	52.00	9270	3644	Delta 30 Deg			
Delta 40 Deg	62.03	8733	5228	Delta 40 Deg			
Delta 50 Deg	72.00	9559	6772				
FMVSS 207 Limit	28.30	3303	165	FMVSS 207 Limit	28.62	3311	165
5% Yield Strength	36.71	8733	1071	5% Yield Strength	36.56	8670	1021
Ultimate Strength	43.52	9972	2213	Work Input	38.11	9126	1272
				Energy Return			-610

	Ford Windstar Passenger			Ford Windstar Driver			
Stiffness = 432 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 484 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.03	4423	405	Delta 10 Deg	32.00	4124	327
Delta 20 Deg	42.03	7966	1543	Delta 20 Deg	42.02	7759	1362
Delta 30 Deg	52.01	9621	3037	Delta 30 Deg			
Delta 40 Deg	62.03	12208	4970	Delta 40 Deg			
Delta 50 Deg	71.99	13527	7207				
FMVSS 207 Limit	29.07	3311	208	FMVSS 207 Limit	30.16	3325	206
5% Yield Strength	40.74	7837	1367	5% Yield Strength	34.57	5130	536
Ultimate Strength	71.99	13527	7207	Work Input	50.08	9821	2637
				Energy Return			-864

	Dodge B250 Van Driver			Dodge B250 Van Passenger			
Stiffness = 471 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 468 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.02	3815	289	Delta 10 Deg	32.02	3730	284
Delta 20 Deg	41.98	6731	1282	Delta 20 Deg	41.98	6588	1251
Delta 30 Deg	52.00	7194	2495	Delta 30 Deg			
Delta 40 Deg	62.01	8338	3827	Delta 40 Deg			
Delta 50 Deg	71.98	9674	5404				
FMVSS 207 Limit	30.91	3297	221	FMVSS 207 Limit	31.05	3321	224
5% Yield Strength	37.16	5913	733	5% Yield Strength	36.19	5418	622

Ultimate Strength	71.98	9674	5404	Work Input	50.39	6942	2265
				Energy Return			-653

	Saab 900S Passenger			Saab 900S Driver			
Stiffness = 1041 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 862 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.02	5946	468	Delta 10 Deg	32.03	4755	337
Delta 20 Deg	42.00	14839	2386	Delta 20 Deg	42.05	12515	1875
Delta 30 Deg	52.00	19944	5468	Delta 30 Deg			
Delta 40 Deg	61.98	13058	8636	Delta 40 Deg			
Delta 50 Deg	71.98	9307	10456				
FMVSS 207 Limit	28.62	3300	192	FMVSS 207 Limit	30.10	3312	202
5% Yield Strength	38.38	12322	1526	5% Yield Strength	40.38	11403	1539
Ultimate Strength	54.55	20300	6372	Work Input	46.16	14478	2881
				Energy Return			-1173

	Ford Contour Passenger			Ford Contour Driver			
Stiffness = 782 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 683 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.02	7320	679	Delta 10 Deg	32.02	6228	512
Delta 20 Deg	42.05	8843	2084	Delta 20 Deg	42.04	8375	1801
Delta 30 Deg	52.00	11636	3846	Delta 30 Deg	52.00	11075	3480
Delta 40 Deg				Delta 40 Deg	62.00	12584	5535
Delta 50 Deg				Delta 50 Deg	71.98	6972	7038
FMVSS 207 Limit	26.24	3322	126	FMVSS 207 Limit	27.78	3295	160
5% Yield Strength	31.45	7024	615	5% Yield Strength	34.46	7483	808
Ultimate Strength				Ultimate Strength	63.76	13052	5923

	Hyundia Sonata Driver			Hyundia Sonata Passenger			
Stiffness = 681 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 632 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.01	4208	274	Delta 10 Deg	32.02	5421	431
Delta 20 Deg	41.99	9188	1516	Delta 20 Deg	42.00	9763	1778

Delta 30 Deg	52.01	10642	3276	Delta 30 Deg			
Delta 40 Deg	61.97	7998	4962	Delta 40 Deg			
Delta 50 Deg	72.01	6059	6160				
FMVSS 207 Limit	30.68	3327	187	FMVSS 207 Limit	28.43	3306	155
5% Yield Strength	37.36	7469	830	5% Yield Strength	33.44	6148	575
Ultimate Strength	54.75	10884	3775	Work Input	46.74	10159	2636
				Energy Return			-914

	Hyundai Accent Passenger			Hyundai Accent Driver			
Stiffness = 616 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 521 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.00	4535	310	Delta 10 Deg	32.02	4030	281
Delta 20 Deg	41.98	8609	1500	Delta 20 Deg	42.02	8644	1417
Delta 30 Deg	52.00	9905	3128	Delta 30 Deg	52.00	10419	3104
Delta 40 Deg	61.98	10929	4949	Delta 40 Deg			
Delta 50 Deg	71.98	8338	6818				
FMVSS 207 Limit	30.09	3281	179	FMVSS 207 Limit	30.61	3278	190
5% Yield Strength	34.66	5788	552	5% Yield Strength	41.44	8477	1333
Ultimate Strength	66.27	11848	5790	Work Input	55.43	9667	3737
				Energy Return			-986

	Nissan Sentra Passenger						
Stiffness = 913 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness =	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.00	6439	443	Delta 10 Deg			
Delta 20 Deg	41.98	12029	2148	Delta 20 Deg			
Delta 30 Deg	52.02	12096	4321	Delta 30 Deg			
Delta 40 Deg	62.00	12141	6443	Delta 40 Deg			
Delta 50 Deg	72.02	12387	8571				
FMVSS 207 Limit	28.55	3309	150	FMVSS 207 Limit			
5% Yield Strength	35.55	9212	934	5% Yield Strength			
Ultimate Strength	47.50	12655	3337	Work Input			
				Energy Return			

	Ford Explorer Driver			Ford Explorer Driver			
Stiffness = 394 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 321 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.01	2679	186	Delta 10 Deg	32.01	2740	209
Delta 20 Deg	41.99	6096	983	Delta 20 Deg	41.99	5836	966
Delta 30 Deg	52.01	8365	2258	Delta 30 Deg	52.01	7945	2193
Delta 40 Deg	62.03	9157	3829	Delta 40 Deg	62.01	9480	3729
Delta 50 Deg	71.99	8966	5338				
FMVSS 207 Limit	33.50	3335	263	FMVSS 207 Limit	33.83	3315	305
5% Yield Strength	39.67	5440	744	5% Yield Strength	45.39	6685	1335
Ultimate Strength	59.97	9239	3498	Work Input			
				Energy Return			

	Honda Passport Passenger			Honda Passport Driver			
Stiffness = 553 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 548 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.03	4463	338	Delta 10 Deg	32.00	5304	488
Delta 20 Deg	41.99	8109	1479	Delta 20 Deg			
Delta 30 Deg	52.01	8507	2921	Delta 30 Deg			
Delta 40 Deg	62.03	7208	4314	Delta 40 Deg			
Delta 50 Deg	72.01	6726	5517				
FMVSS 207 Limit	29.84	3332	193	FMVSS 207 Limit	27.91	3307	181
5% Yield Strength	35.05	5846	612	5% Yield Strength	32.19	5345	506
Ultimate Strength	50.94	8549	2762	Work Input	41.82	7134	1654
				Energy Return			-588

	Honda Passport #2 Driver			Honda Passport #2 Passenger			
Stiffness = 590 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 586 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.03	5440	485	Delta 10 Deg	32.00	4827	497
Delta 20 Deg	41.98	8348	1694	Delta 20 Deg			
Delta 30 Deg	51.99	8851	3225	Delta 30 Deg			
Delta 40 Deg	62.01	8411	4725	Delta 40 Deg			
Delta 50 Deg	71.99	8160	6164				
FMVSS 207 Limit	27.96	3348	169	FMVSS 207 Limit	27.76	3358	169

5% Yield Strength	31.94	5377	479	5% Yield Strength	31.53	4554	461
Ultimate Strength	49.12	8997	2776	Work Input	41.62	7996	1619
				Energy Return			-631

	Dodge Neon Passenger			Dodge Neon Driver			
Stiffness = 458 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 327 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.02	3978	320	Delta 10 Deg	32.02	3472	276
Delta 20 Deg	41.98	7525	1346	Delta 20 Deg	42.02	6970	1205
Delta 30 Deg	52.00	8918	2847	Delta 30 Deg			
Delta 40 Deg	61.98	6511	4154	Delta 40 Deg			
Delta 50 Deg	71.98	5903	5233				
FMVSS 207 Limit	30.52	3319	226	FMVSS 207 Limit	31.51	3320	247
5% Yield Strength	36.03	5549	660	5% Yield Strength			
Ultimate Strength	50.40	9197	2592	Work Input	42.82	7122	1312
				Energy Return			-505

	Dodge Intrepid Driver			Dodge Intrepid Passenger			
Stiffness = 501 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 357 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.02	3040	206	Delta 10 Deg	32.03	2325	166
Delta 20 Deg	42.00	7729	1172	Delta 20 Deg	42.00	5163	844
Delta 30 Deg	52.00	10019	2744	Delta 30 Deg			
Delta 40 Deg	62.00	9292	4483	Delta 40 Deg			
Delta 50 Deg	71.98	8114	5974				
FMVSS 207 Limit	32.49	3318	233	FMVSS 207 Limit	34.66	3307	296
5% Yield Strength	41.96	7686	1169	5% Yield Strength	36.14	3627	387
Ultimate Strength	55.28	10255	3325	Work Input	46.13	5632	1244
				Energy Return			-381

	Isuzu Rodeo Passenger			Isuzu Rodeo Driver			
Stiffness = 524 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 561 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.02	4519	370	Delta 10 Deg	32.00	3608	268

Delta 20 Deg	42.00	7869	1436	Delta 20 Deg	42.00	6208	1086
Delta 30 Deg	52.00	9039	2956	Delta 30 Deg			
Delta 40 Deg	62.00	8555	4480	Delta 40 Deg			
Delta 50 Deg	72.03	8817	5982				
FMVSS 207 Limit	29.34	3309	189	FMVSS 207 Limit	30.89	3305	199
5% Yield Strength	32.58	4701	418	5% Yield Strength	31.96	3668	264
Ultimate Strength	49.63	9099	2581	Work Input	42.73	6167	1163
				Energy Return			-457

	Chrysler Cirrus Passenger			Chrysler Cirrus Driver			
Stiffness = 373 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 358 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.02	2038	140	Delta 10 Deg	32.02	2038	144
Delta 20 Deg	42.00	5616	821	Delta 20 Deg	42.04	5314	802
Delta 30 Deg	52.00	8154	2032	Delta 30 Deg			
Delta 40 Deg	62.00	8633	3551	Delta 40 Deg			
Delta 50 Deg	72.03	6995	4876				
FMVSS 207 Limit	35.36	3298	296	FMVSS 207 Limit	35.49	3296	306
5% Yield Strength	43.78	6115	1000	5% Yield Strength	40.84	4954	695
Ultimate Strength	58.49	8893	3007	Work Input	49.47	6632	1615
				Energy Return			-643

	Ford Taurus Driver			Ford Taurus Passenger			
Stiffness = 518 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 444 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.00	2039	140	Delta 10 Deg	32.00	2940	210
Delta 20 Deg	42.05	6671	931	Delta 20 Deg	42.01	7338	1139
Delta 30 Deg	52.01	9575	2359	Delta 30 Deg			
Delta 40 Deg	62.03	7912	3954	Delta 40 Deg			
Delta 50 Deg	72.01	8644	5326				
FMVSS 207 Limit	34.47	3302	255	FMVSS 207 Limit	32.65	3293	246
5% Yield Strength	40.06	5896	712	5% Yield Strength	43.25	7736	1300
Ultimate Strength	55.22	10217	2914	Work Input	45.17	8090	1570
				Energy Return			-758

	Pontiac Sunfire Passenger			Pontiac Sunfire Driver			
Stiffness = 371 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 341 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.00	3019	241	Delta 10 Deg	32.02	2350	175
Delta 20 Deg	42.00	5545	995	Delta 20 Deg	41.98	6027	922
Delta 30 Deg	52.00	6818	2053	Delta 30 Deg	52.00	8377	2197
Delta 40 Deg	62.03	8153	3386	Delta 40 Deg			
Delta 50 Deg	72.01	8379	4833				
FMVSS 207 Limit	32.99	3306	295	FMVSS 207 Limit	34.16	3310	281
5% Yield Strength	32.99	3286	295	5% Yield Strength	47.57	7519	1581
Ultimate Strength	67.55	8379	4181	Work Input			
				Energy Return			

	Chevy Blazer Driver			Chevy Blazer Passenger			
Stiffness = 364 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 459 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.02	3361	281	Delta 10 Deg	32.02	3750	289
Delta 20 Deg	42.00	6848	1181	Delta 20 Deg	41.98	7224	1269
Delta 30 Deg	52.00	8655	2564	Delta 30 Deg	52.00	8728	2687
Delta 40 Deg	62.00	8928	4120	Delta 40 Deg	62.01	8686	4219
Delta 50 Deg	72.01	8697	5650				
FMVSS 207 Limit	31.76	3298	266	FMVSS 207 Limit	31.00	3284	226
5% Yield Strength	43.97	7353	1426	5% Yield Strength	43.59	7605	1469
Ultimate Strength	57.93	8991	3487	Work Input	70.06	8071	5437
				Energy Return			-927

	Mazda Protégé Passenger			Mazda Protégé Driver			
Stiffness = 523 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 436 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.00	4325	331	Delta 10 Deg	32.00	4306	415
Delta 20 Deg	42.03	6021	1273	Delta 20 Deg	42.02	7577	1445
Delta 30 Deg	51.99	9497	2631	Delta 30 Deg			
Delta 40 Deg	62.01	7992	4262	Delta 40 Deg			
Delta 50 Deg	71.99	5851	5453				
FMVSS 207 Limit	29.95	3286	195	FMVSS 207 Limit	29.00	3314	220

5% Yield Strength	33.55	4897	457	5% Yield Strength	29.79	3546	267
Ultimate Strength	55.03	10345	3162	Work Input	50.31	7809	2663
				Energy Return			-811

	Toyota 4-Runner Driver			Toyota 4-Runner Passenger			
Stiffness = 935 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 834 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.02	5169	308	Delta 10 Deg	32.00	7708	674
Delta 20 Deg	42.00	10316	1822	Delta 20 Deg			
Delta 30 Deg	52.00	5916	3214	Delta 30 Deg			
Delta 40 Deg	62.02	3780	4073	Delta 40 Deg			
Delta 50 Deg	72.02	3588	4701				
FMVSS 207 Limit	29.92	3311	153	FMVSS 207 Limit	26.41	3291	124
5% Yield Strength	34.98	7582	654	5% Yield Strength	32.26	7815	709
Ultimate Strength	40.24	10658	1499	Work Input	35.60	8940	1220
				Energy Return			-494

	Nissan Maxima Passenger						
Stiffness = 887 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness =	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	31.98	7376	560	Delta 10 Deg			
Delta 20 Deg	41.98	11988	2384	Delta 20 Deg			
Delta 30 Deg				Delta 30 Deg			
Delta 40 Deg				Delta 40 Deg			
Delta 50 Deg							
FMVSS 207 Limit	27.44	3298	13	FMVSS 207 Limit			
5% Yield Strength	35.97	10362	1180	5% Yield Strength			
Ultimate Strength	45.18	12857	3144	Work Input			
				Energy Return			

	Mazda Millenia Driver			Mazda Millenia Passenger			
Stiffness = 776 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 1191 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.00	5160	384	Delta 10 Deg	32.00	9947	796

Delta 20 Deg	41.98	10925	1866	Delta 20 Deg	42.00	15119	3124
Delta 30 Deg	52.01	14412	4060	Delta 30 Deg	52.00	16982	5997
Delta 40 Deg	62.03	15993	6790	Delta 40 Deg	61.98	16354	8900
Delta 50 Deg	72.01	18759	9830	Delta 50 Deg	72.01	15165	11543
FMVSS 207 Limit	29.35	3301	194	FMVSS 207 Limit	25.92	3308	88
5% Yield Strength	37.40	8903	1003	5% Yield Strength	28.53	5987	312
Ultimate Strength	72.01	18759	9830	Ultimate Strength	49.56	17448	5264

	Chevy T-600 Van Passenger			Chevy T-600 Van Driver			
Stiffness = 300 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)	Stiffness = 256 in-lb/deg	Angle (deg.)	Moment (in-lbs)	Work (in-lbs)
Delta 10 Deg	32.02	3141	272	Delta 10 Deg	32.02	3407	281
Delta 20 Deg	42.02	5872	1079	Delta 20 Deg	42.00	6106	1119
Delta 30 Deg	52.00	8467	2334	Delta 30 Deg	52.00	8450	2405
Delta 40 Deg	62.00	9914	3954	Delta 40 Deg			
Delta 50 Deg	72.02	10160	5726				
FMVSS 207 Limit	32.45	3305	297	FMVSS 207 Limit	31.70	3298	262
5% Yield Strength	41.85	5817	1062	5% Yield Strength	55.15	9022	2887
Ultimate Strength	68.58	10297	5113	Work Input	56.95	8831	3186
				Energy Return			-851